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EVALUATION OF THE C/EC/KC-135 GROUND COLLISION AVOIDANCE SYSTEM (GCAS) (STUDY 1)

Justin D. Rueb, Major, USAF
John A. Hassoun

Crew Station Evaluation Facility
Crew Systems Division
ASD/ENEC

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John A. Hassoun
Program Manager
Crew Station Evaluation Facility

Robert Billings
Technical Expert
Crew Systems Division

FOR THE COMMANDER

John W. Vogt, Jr., Lt Col, USAF
Acting Director, Support Systems Engrg

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In support of the KC-135 Avionics Modernization Program, subjective and performance data were collected in order to provide the Government and contractor engineers with information needed in the design of a Ground Collision Avoidance System (GCAS) for all C/EC/KC-135 aircraft. The GCAS will serve to alert the crew of an impending ground impact. This decision will be based on data collected from various aircraft sensors (e.g., radio altimeter). The GCAS, due to the downward looking nature of the radio altimeter, will not be as effective as a forward looking Terrain Following Radar (TFR) and would only serve to complement this system.

This evaluation was Study 1 of a two-part study. Study 1 was comprised of four phases. Throughout the four phases, concerns and recommendations were forwarded to the System Program Office and to the Cubic Corporation. This resulted in modification of the algorithm prior to the next phase of the evaluation.

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Phase I efforts focused on the verification and validation of the algorithm. This phase simply established how well the algorithm predicted altitude loss based on current inputs. Phase II was the Robot Pilot Model phase. During this phase, a computer pilot model tested the GCAS under different aircraft configurations and environmental conditions. The man-in-the-loop phase, Phase III, used a subset of the configurations in Phase II to determine the algorithm's ability to accurately predict under realistic conditions. In the final phase, current operational pilots flew mission scenarios based on selected CFIT mishaps. This phase permitted an evaluation of the Cubic GCAS algorithm under real time conditions. The following are the Study 1 recommendations:

1. The effects of Cg should be considered by the algorithm.

2. The algorithm should be adjusted to better account for the effects of slope.

3. The algorithm should cover a flight path angle range of 20 degrees nose down to 15 degrees nose up.

4. The algorithm should provide a warning for glideslope deviations to the high side of glideslope.

5. The algorithm should provide a minimum ground clearance of 150 feet (AGL) and a maximum ground clearance of 1000 feet (AGL). A general rule of thumb is approximately 10% of the downward vertical velocity of the aircraft at warning initiation.

6. Measures should be included to inhibit the pull-up message for possible bounces on the runway during landing.

7. Finally, if the approach and landing algorithm is intended to provide the pilot adequate time to effectively land the aircraft, then the gear and flap warnings should begin at 1000 feet (AGL), instead of the 500 feet currently used by the algorithm.

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INTRODUCTION

Background

During 1976, the Federal Aviation Administration (FAA) required all commercial airliners to be equipped with Ground Proximity Warning Systems (GPWS). Such a system is designed to enhance flight safety, particularly during the takeoff and approach/landing phases of flight. Since that time, Controlled Flight into Terrain (CFIT) mishaps for commercial airliners have been near zero. The Air Force similarly became interested in GPWS systems for its potential life and cost saving benefits. Earlier focus was on the development of GPWS and Ground Collision Avoidance Systems (GCAS) for fighter-type aircraft. GPWS/GCAS systems have been incorporated or are being incorporated into the A-7, A-10, F-16, and F-111 aircraft. However, little attention has been directed toward GCAS development for cargo/transport/tanker aircraft.

From 1970-1989, United States Air Force cargo/transport/tanker aircraft have been involved in thirty-one Controlled Flight Into Terrain (CFIT) mishaps. A review of these mishaps (Rueb & Kinzig, 1989; Appendix A) revealed that over 50% of the accidents may have been prevented by an operable Ground Collision Avoidance System (GCAS). In an effort to prevent similar mishaps, the Air Force is investigating the plausibility of incorporating a GCAS system into cargo/transport/tanker type aircraft.

Air Force's Strategic Air Command (SAC Statement of Need (SON), 1987) and Military Airlift Command (MAC SON, 1987) have established a user need for a large body aircraft GCAS system. Accordingly, Air Force Logistics Command (AFLC) contracted the Cubic Corporation of San Diego to develop a generic GCAS system for implementation into the cargo/transport/tanker fleet. This report is Part 1 of a two-part study conducted to evaluate the effectiveness and accuracy of the Cubic GCAS algorithm.

GCAS System Design

GCAS systems generally use software algorithms to compute the altitude for emergency warning onset based on aircraft sensor inputs such as airspeed and altitude. Two considerations are important in designing the system. First, emphasis is placed on minimizing false alarms/nuisance warnings. These occur when the pilot has not committed a ground clearance error, yet a warning is generated. The second concern requires a warning to be generated whenever a ground clearance error has been committed.

Nuisance warnings may be the result of three factors. Erroneous sensor input could cause a false alarm and is a consequence of the algorithm's level of sophistication. Another factor is the algorithm's ability to predict pilot reaction time. Pilot reaction time is the elapsed time interval between the system's recognition of a ground clearance error (warning initiation) and the pilot's initiation of the recovery maneuver. For example, reaction time differences (predicted v. actual) of just one second for a steep dive (12,000 feet per minute) could add an extra 200 feet to the predicted total altitude loss. Finally, the algorithm's inability to accurately predict, calculate, or extrapolate could also cause a nuisance warning.

GCAS algorithms usually are designed using one of two approaches. The first approach used by Cubic's Ground Collision Avoidance System (Cubic, 1985) and Fairchild's Low Altitude Warning System (Shah, 1988) is based on a set of generic aerodynamic equations. These algorithms may differ in the various assumptions (e.g., G-load, roll and pitch limits, pilot reaction time) used to calculate predicted altitude loss. General Dynamic's (GD) Enhanced Ground Clobber uses the second approach. This

approach uses algorithms based on form functions (sometimes called curve fitting) empirically derived by off-line simulation. The Cubic GCAS algorithm evaluated in this report followed the first approach.

GCAS Evaluation Procedure

The Cubic GCAS algorithm was evaluated in four phases. Throughout the four phases, concerns and recommendations were forwarded to the System Program Office and to the Cubic Corporation. This resulted in modification of the algorithm prior to the next phase of the evaluation.

Phase I efforts focused on the verification and validation of the algorithm. This phase simply established how well the algorithm predicted altitude loss based on current inputs. Phase II was the Robot Pilot Model phase. During this phase, a computer pilot model tested the GCAS under different aircraft configurations and environmental conditions.

The man-in-the-loop phase, Phase III, used a subset of the configurations in Phase II to determine the algorithm's ability to accurately predict under realistic conditions (human reaction times). In the final phase, current operational pilots flew mission scenarios based on selected CFIT mishaps. This phase permitted an evaluation of the Cubic GCAS algorithm under real world conditions.

Cubic GCAS

The Cubic algorithm is comprised of four main subroutines labeled GCASALRT, GCASDIVE, GCASROLL, and GCASLAND. GCASALRT computes the altitude loss due to pilot response (reaction) time. GCASDIVE computes the altitude loss as a result of the Dive/Climb Angle (DCA) of the aircraft. GCASROLL computes the altitude loss due to aircraft roll configuration. These three subroutines, GCASALRT, GSASDIVE, and GCASROLL, in addition to a safety buffer, are then summed to make the total predicted altitude loss (TALTLS). The resulting total is compared with the actual aircraft altitude and a warning is activated if the actual aircraft altitude is less than the algorithm derived total altitude (MSGESTAT). The GCASLAND subroutine activates the TCHDWN subroutine which generates a warning when certain conditions are encountered during approach and landing (explained later). No computation of altitude is performed. These algorithms are addressed by the message warning subroutine labeled MSGESTAT. See Figure 1 for the flow diagram of the Cubic algorithm.

The GCASALRT algorithm uses the available flight path angle, vertical acceleration, and vertical velocity inputs in deriving the altitude loss due to pilot response time (Figure 2). It uses the equation: $DELTAZ = RESP * Vz + .5(AZ * RESP^2)$. If Δ ALT (altitude change) is negative (losing altitude), then the computed GCASALRT altitude is used; otherwise, the GCASALRT altitude is set to zero. The GCASALRT algorithm addresses the sub-algorithm, PILTRESP. PILTRESP computes the predicted pilot response (RESP) based on the current g-load factor. Predicted PILTRESP times could vary from 0.3 second to 1.0 second.

The GCASDIVE subroutine uses the inputs of angle of attack, bank angle, barometric pressure, equivalent airspeed, flight path angle, g-load, true airspeed, vertical acceleration, and vertical velocity in the time-to-recover and time-to-target g-load equations to generate the predicted altitude loss due to dive recovery (Figure 3). If the time-to-recover is less than the time-to-target g-load, then altitude loss is based on the time-to-recover

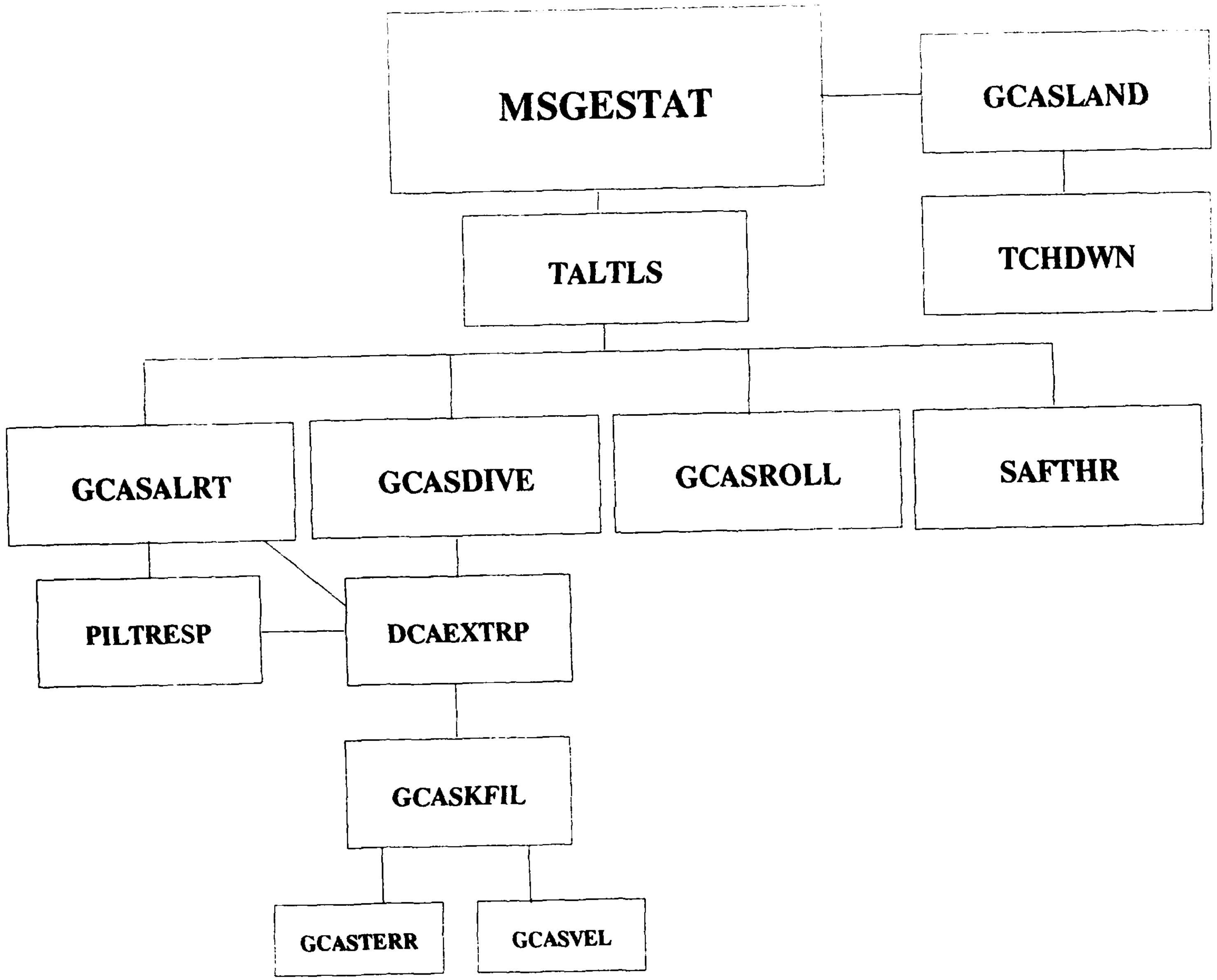


Figure 1. Flow diagram for the Cubic algorithm.

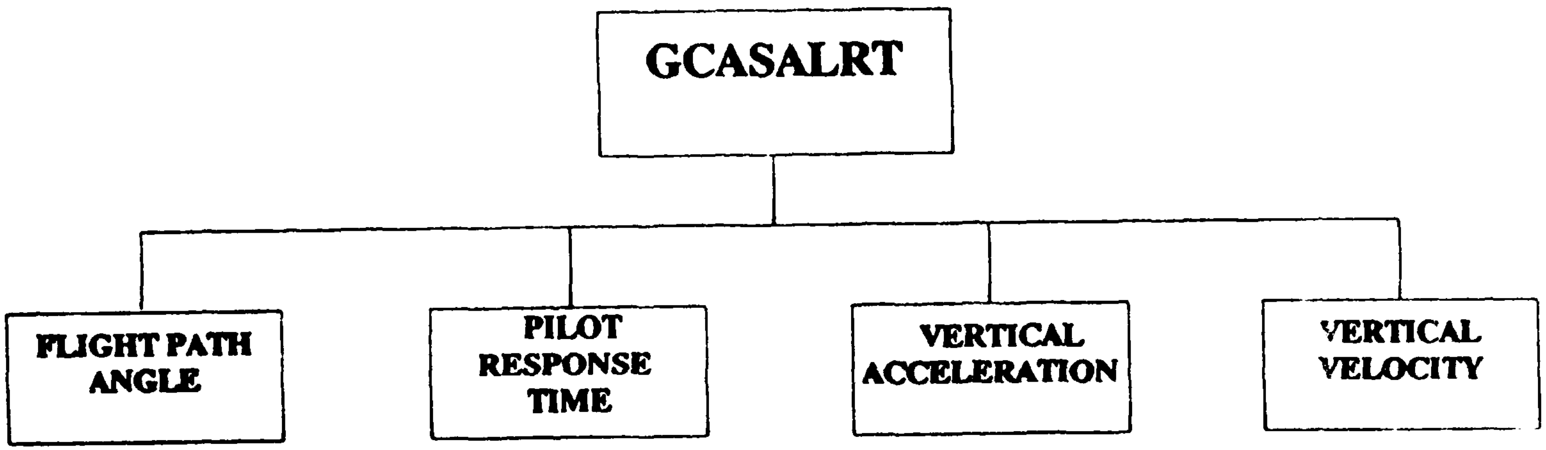


Figure 2. GCASALRT sub-algorithm and required aircraft inputs.

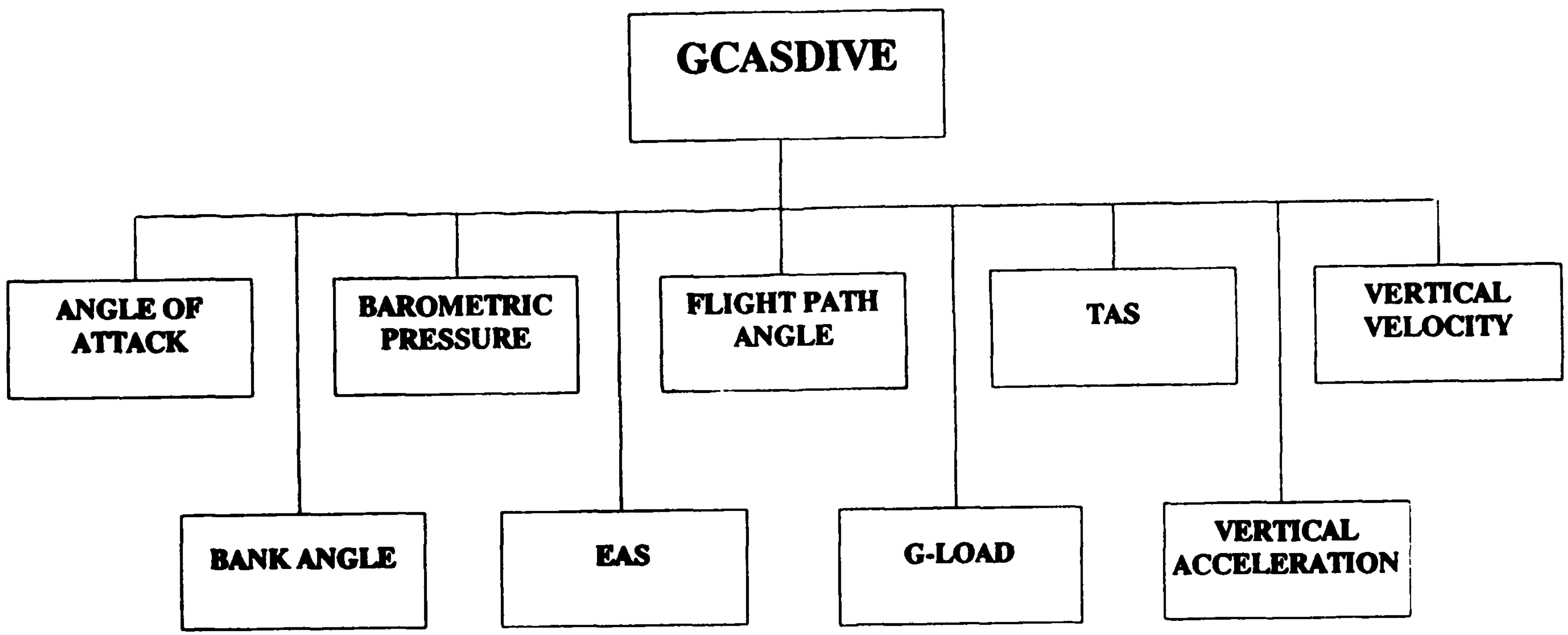


Figure 3. GCASDIVE sub-algorithm and required aircraft inputs.

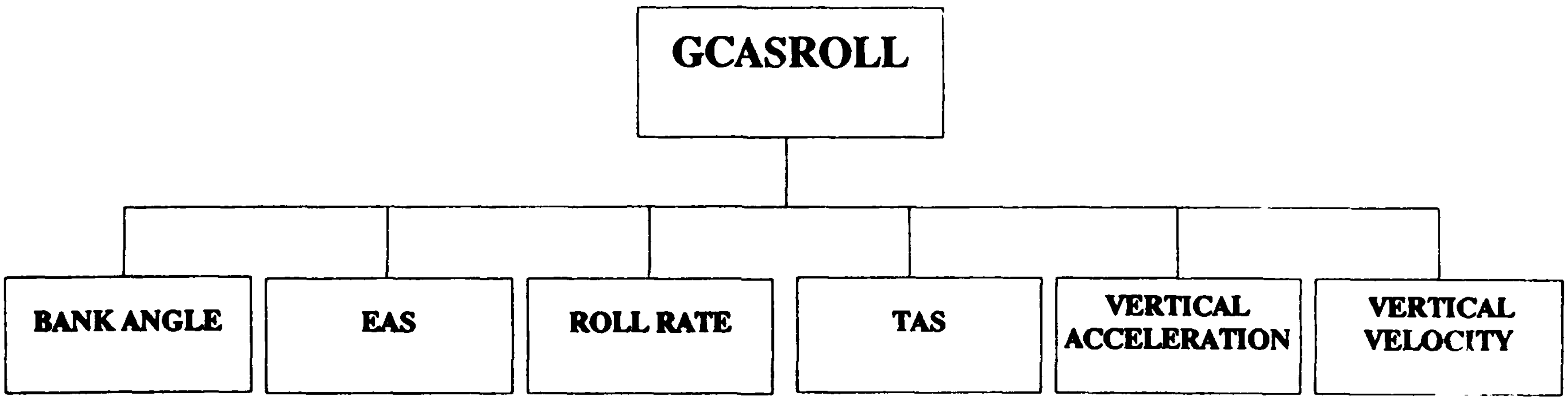


Figure 4. GCASROLL sub-algorithm and required aircraft inputs.

equations; otherwise, the altitude is calculated based on the time-to-target g-load. The GCASDIVE algorithm also addresses directly or indirectly the following sub-algorithms: DCAEXTRP, GCASKFIL, GCASVEL, and GCASTERR to validate the reliability of the information being used within the program. Specifically, DCAXTRP computes the extrapolated incremental Dive Climb Angle (DCA) which is added to the actual DCA to allow for the effects of terrain slope. For response times not greater than one second, the DCA is extrapolated in one of two ways: (1) Using vertical velocity (Vz) and change in terrain, and (2) Using Vz and vertical acceleration (Az). The method used is dependent on the dive angle. GCASKFIL, a subroutine of DCAXTRP, provides filtering of raw radar altimeter inputs. The Kalmen filter (GCASKFIL) also provides above ground level (AGL) reference during periods when the radar altitude measurement is degraded (e.g., radar altimeter interference). It uses the flight path angle (Gamma) and bank angle to calculate the extrapolation time. It also addresses two of its own subroutines, GCASTERR and GCASVEL. These subroutines provide height Above Ground Level (AGL) and height above Mean Sea Level (MSL) acceptance used to ensure radar altimeter accuracy.

The GCASROLL subroutine (Figure 4) uses aircraft bank angle, equivalent airspeed, roll rate, true airspeed, vertical acceleration, and vertical velocity inputs to compute the predicted altitude loss due to roll recovery. Roll angles from 5° to 45° are covered by the subroutine. Roll angles less than 5° are considered to have no effect on altitude loss. Roll angles greater than 45° are assumed to have the same effect as the 45° roll angle.

The resulting altitudes from GCASALRT, GCASDIVE, and GCASROLL are then summed with a safety buffer altitude calculated in the subroutine SAFTHR, (TALTLS = GCASALRT + GCASDIVE + GCASROLL + SAFTHR). If the total computed altitude does not exceed the actual aircraft altitude (AGL), then MSGESTAT will not generate a warning. However, should the total computed altitude exceed that of the aircraft, then a GCAS warning will be triggered by the MSGESTAT algorithm.

The GCASLAND subroutine activates the TCHDWN subroutine when the aircraft altitude is less than 1000 feet (AGL), and two of the following three conditions are met: (1) Equivalent airspeed is less than 190 knots, (2) Flaps are greater than 30% deployed, and (3) Gear are more than 50% deployed. If the above conditions are not met, then the MSGESTAT subroutine will not be activated by the GCASLAND subroutine. If the conditions above are satisfied, then the TCHDWN subroutine is activated and the aircraft is considered to be prepared for the approach and landing phase of flight. When TCHDWN is activated, several different warnings ("flaps," "gear," "glideslope," & "pull-up") may be activated. These warnings are based on the different conditions of aircraft altitude, glideslope deviation, equivalent airspeed, and gear and flap deployment.

The glideslope warning should be issued when the following four conditions are met: (1) Aircraft altitude exceeds 250 feet (AGL), but is less than 1000 feet AGL, (2) Equivalent airspeed is less than 190 knots, (3) The flaps or the gear or both are deployed beyond the limits described previously, and (4) Deviation from glideslope is less than three dots, but not less than two dots (1 dot = .375 degrees). If the altitude is less than or equal to 100 feet (AGL), then the TCHDWN subroutine is ignored and message warning would be based on the computed altitude loss (TALTLS). If aircraft altitude is greater than 100 feet and less than or equal to 250 feet, or the altitude is between 250-1000 feet and glideslope deviation is not less than three dots, then the message warning would be based on a computed altitude generated by a modified GCASDIVE subroutine. However, if the aircraft is between 250-1000 feet (AGL) and glideslope deviation exceeds two dots but is less than three dots, then a glideslope warning would be issued.

A gear warning is generated when: (1) Aircraft altitude is less than 500 feet (AGL), (2) Flaps are more than 30%, (3) Equivalent airspeed is less than 190 knots, and (4) Gear are not greater than 50% deployed. A flaps warning is generated when: (1) Aircraft altitude is less than 500 feet (AGL), (2) Gear are deployed more than 50%, (3) Equivalent airspeed is less than 190 knots, and (4) Flaps are not greater than 30%. The glideslope, flaps, and gear warnings in the TCHDWN subroutine are automatically generated when the above conditions are met. No computation of altitude is performed for these warnings.

PHASE I

Method

Procedure

The Cubic GCAS algorithm was initially broken down into its different subroutines to determine the aircraft inputs needed by each of the subroutines to compute its predicted altitude loss. As seen in Figures 2-4, the GCASALRT, GCASDIVE, and GCASROLL subroutines require many of the same inputs. After the required inputs were determined, the subroutines were then subjected to a computation analysis requiring each subroutine to compute predicted altitude loss given the different aircraft configurations. A Gould Sel 87 computer connected to a Nicolet Zeta 824/836 CS plotter generated the predicted altitude lost graphs for each of the main subroutines. These altitude-lost graphs were plotted for varying levels of gamma, roll, g-load, altitude, slope, and indicated airspeed, for each of the sub-algorithms. The actual independent variables varied from graph to graph for each of the GCASALRT, GCASDIVE, and GCASROLL subroutines dependent upon the variables used by the subroutine in calculating the predicted altitude loss. The graphs were then analyzed for any discrepancies from that logically expected to occur. For example, if gamma were decreased (dive angle increases), one would logically expect the predicted altitude loss to increase.

Results

GCASALRT

Figure 5 provides an example of the predicted altitude loss due to pilot reaction time (GCASALRT) given a pilot response time of .65; true airspeeds (TAS) of 125, 175, 225, 275, and 325; and flight path angles (Gamma) ranging from 0° to 30° nose down. As we hypothesized, predicted altitude loss increased as both airspeed and gamma increased. Similar trends were exhibited for pilot response times of .72, .79, .86, .93, and 1.00 (Figures 6-10).

GCASDIVE

The GCASDIVE subroutine was evaluated by generating various predicted altitude lost graphs based on a Cg=22; slopes of 0, 6, and 12; barometric altitudes of 1000, 10,000, and 19,000; g-loads of .5, 1.25, and 2.0; airspeeds of 125, 175, 225, 275, and 325 knots; and gammas ranging from 0°-30°. Predicted altitude loss due to flight path angle (GCASDIVE) graphs are shown in Figures 11-13. As seen by the 275 and 325 TAS data lines, there is some interaction of the higher airspeeds with the middle airspeed of 225 between 0 and 13 degrees gamma for the lower g-load conditions. The g-load variable is the g-load of the aircraft at warning initiation. However, this interaction disappears at g-loads of 1.25 and 2.00 (Figures 12 & 13). Further inspection of these graphs reveals gamma and airspeed increases resulted in increased predicted altitude lost, as hypothesized. Additionally, Figures 11, 12, and 13 reveal g-load had an effect on GCASDIVE, but it was interactive in nature, as the predicted altitude loss was higher for both the low (.5) and the high (2.0) g-load conditions, than for the middle (1.25) g-load condition.

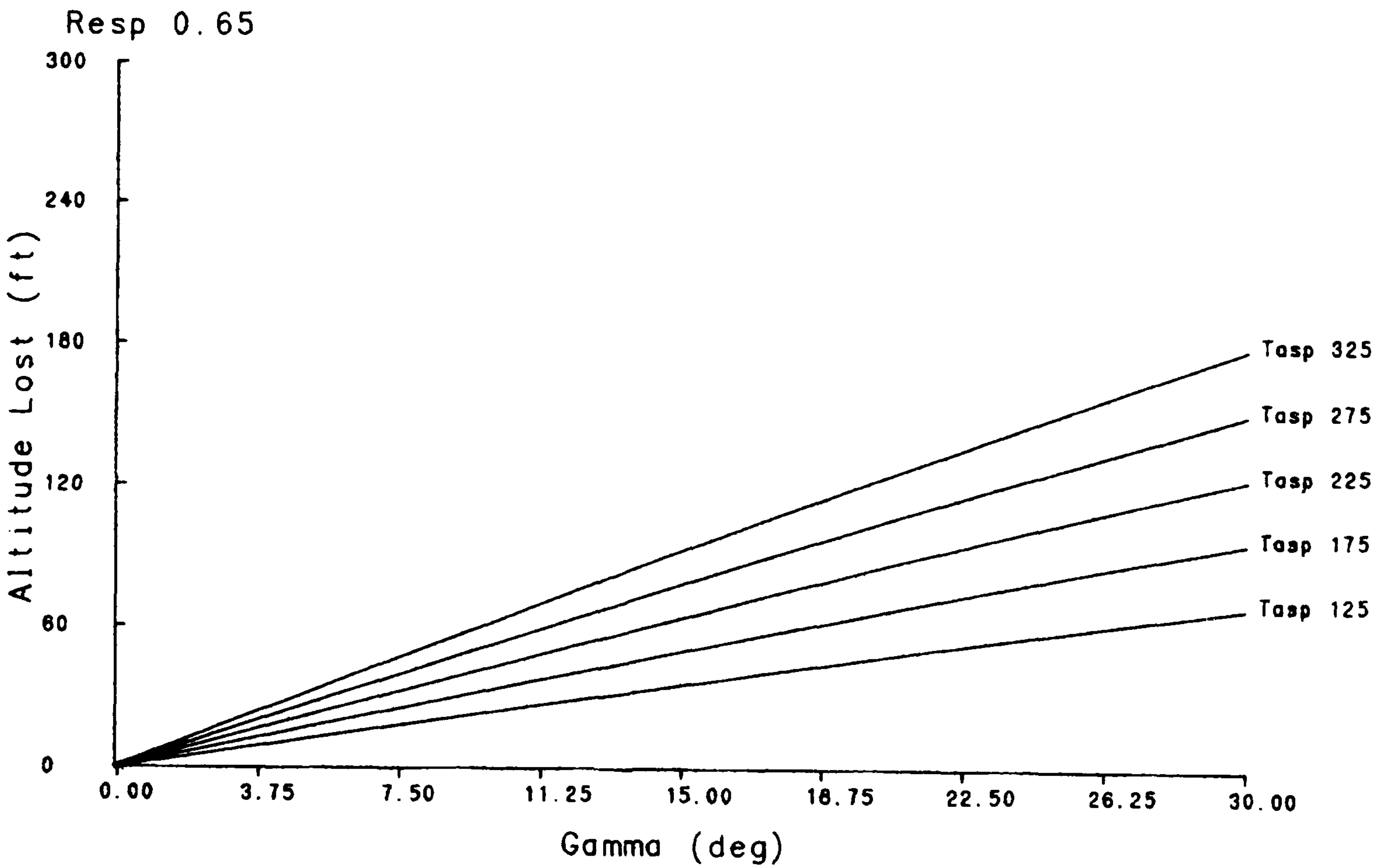


Figure 5. GCASALRT predicted altitude lost as a function of gamma for a pilot response of .65.

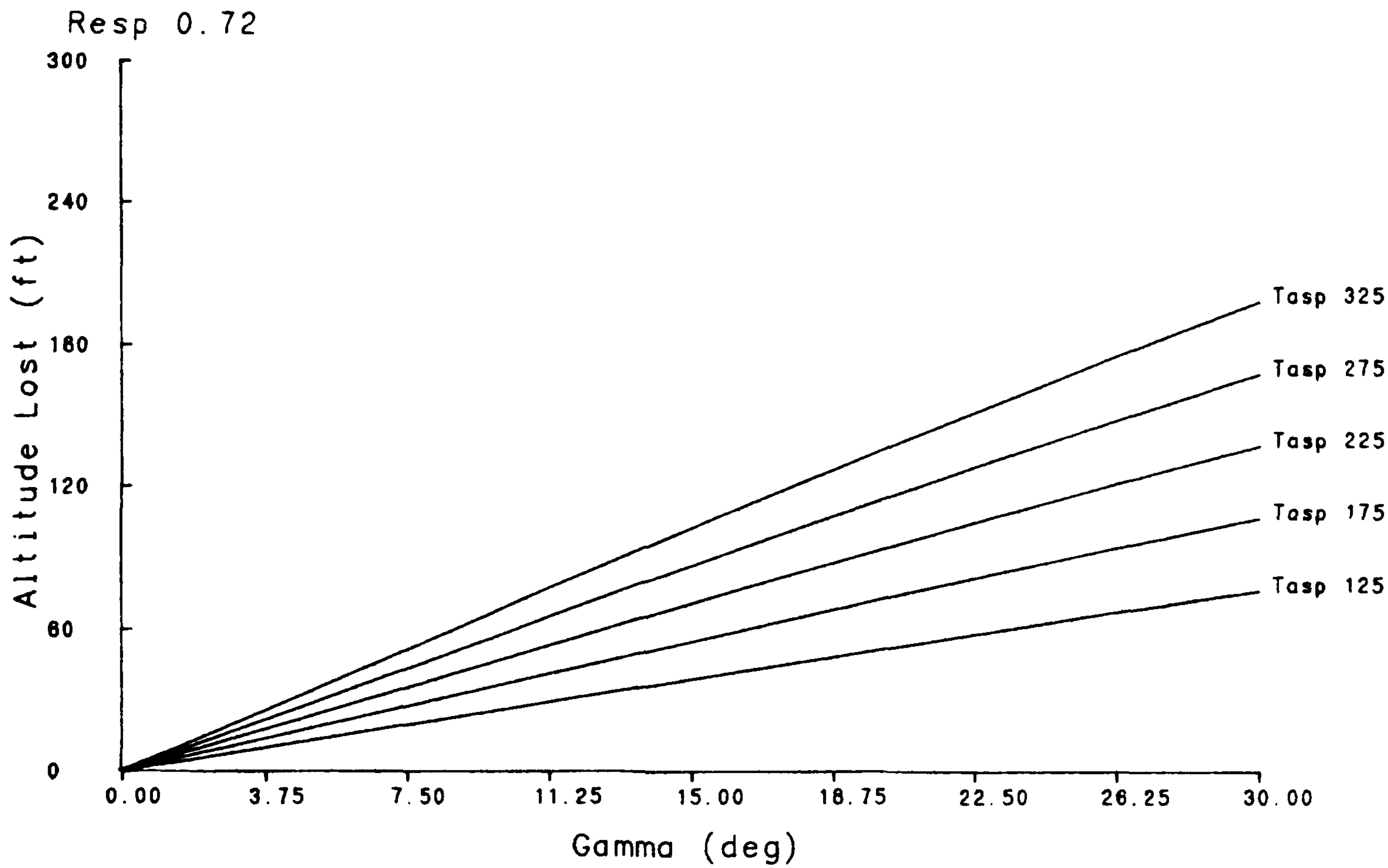


Figure 6. GCASALRT predicted altitude lost as a function of gamma for a pilot response of .72.

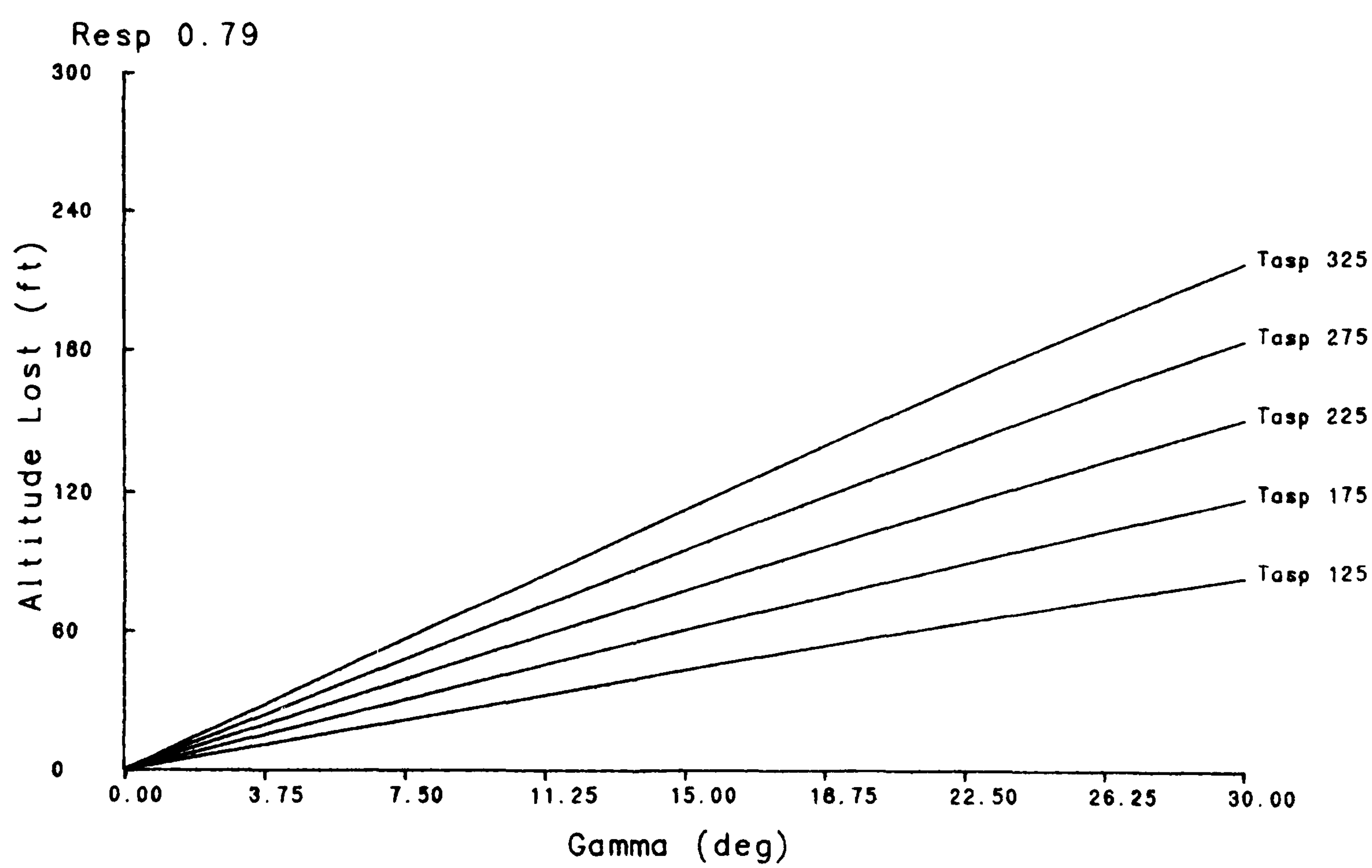


Figure 7. GCASALRT predicted altitude lost as a function of gamma for a pilot response of .79.

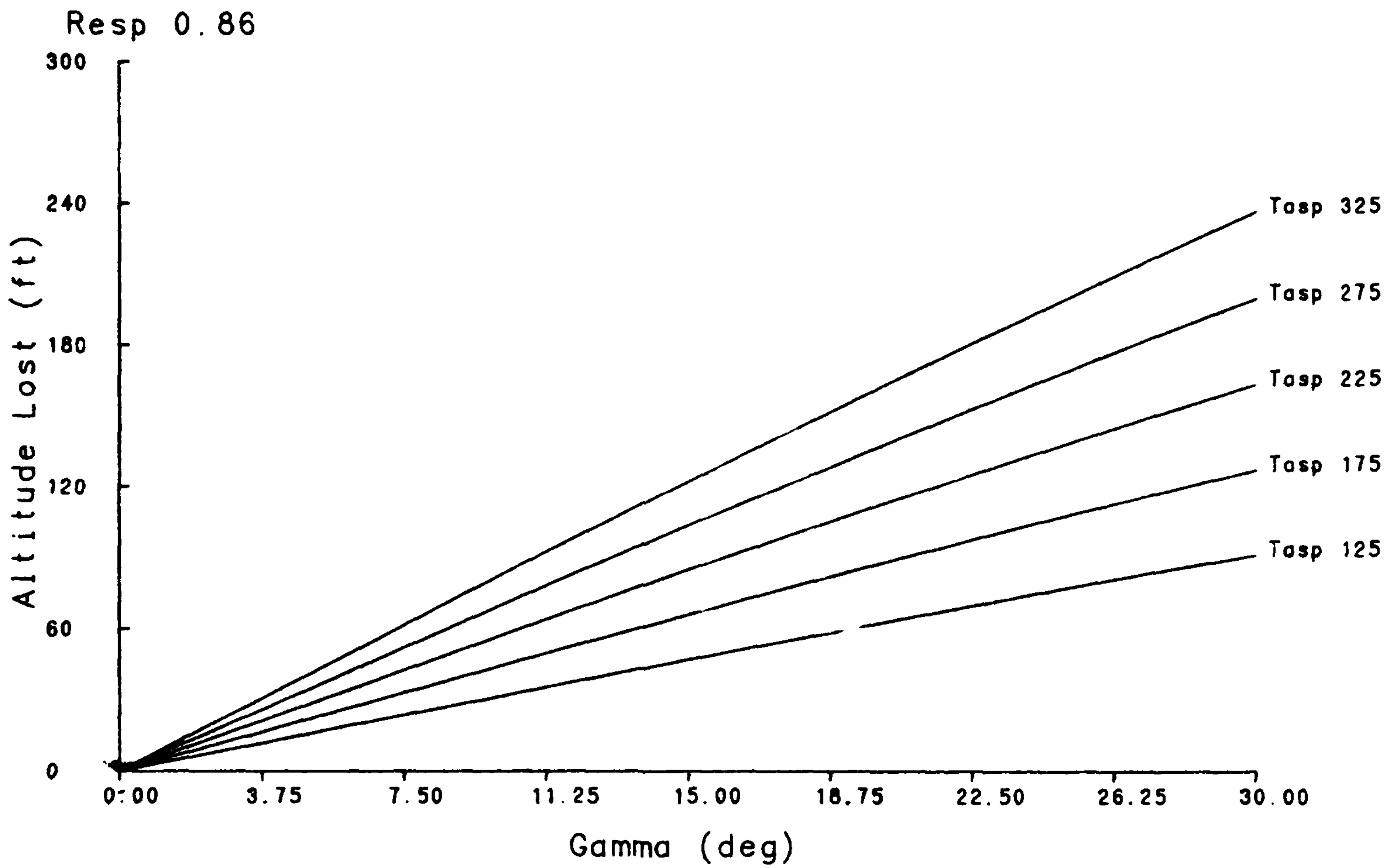


Figure 8. GCASALRT predicted altitude lost as a function of gamma for a pilot response of .86.

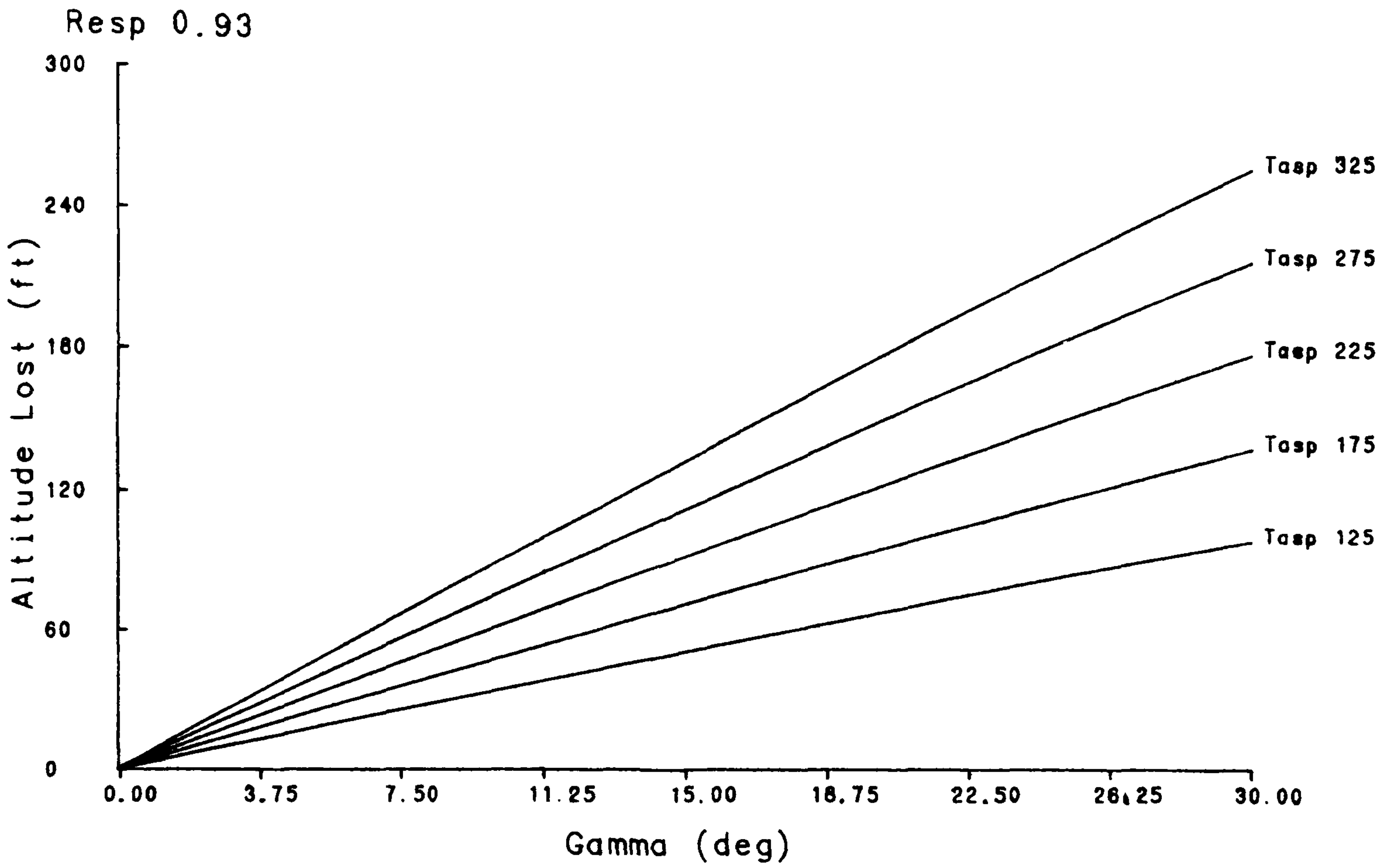


Figure 9. GCASALRT predicted altitude lost as a function of gamma for a pilot response of .93.

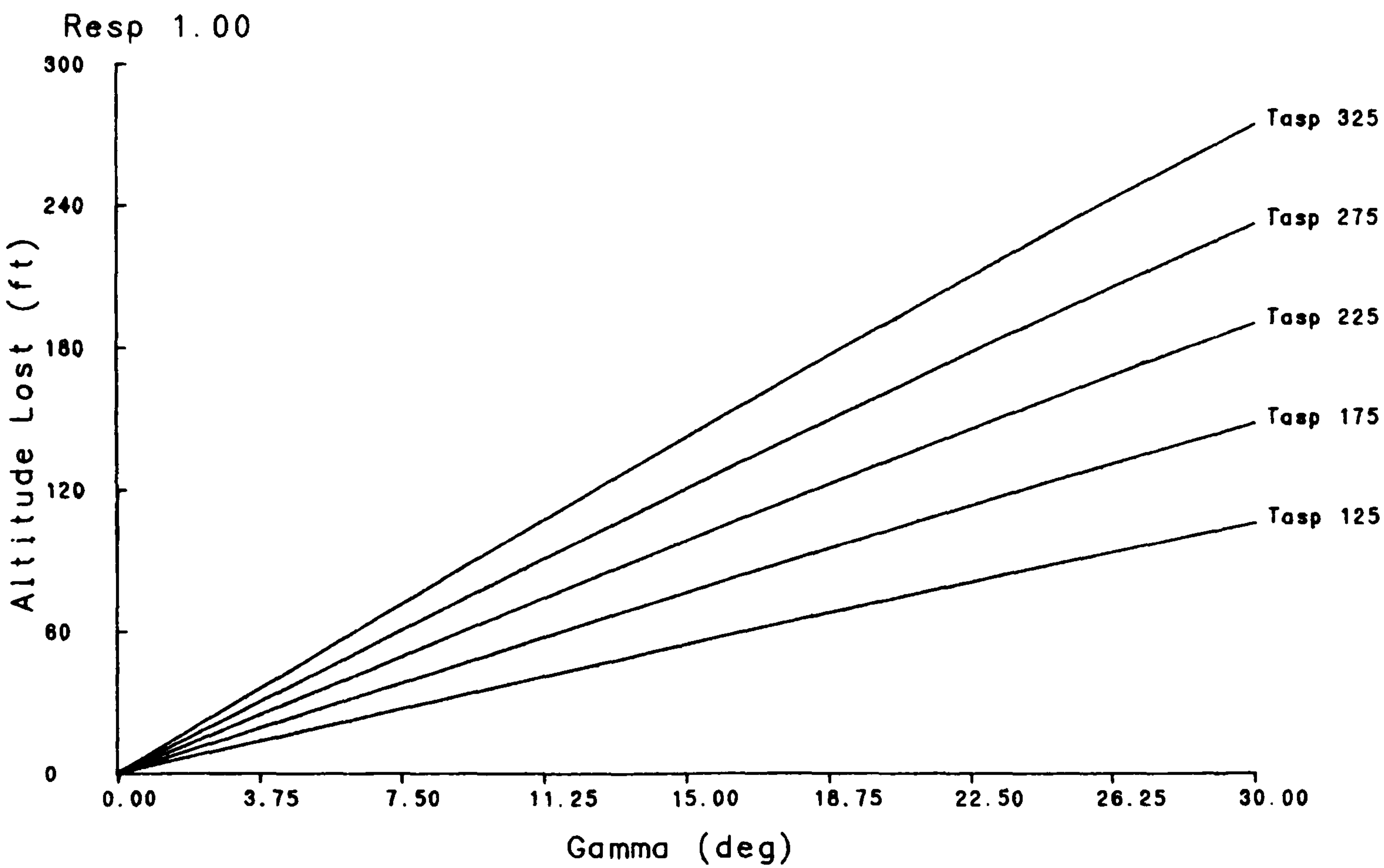


Figure 10. GCASALRT predicted altitude lost as a function of gamma for a pilot response of 1.00.

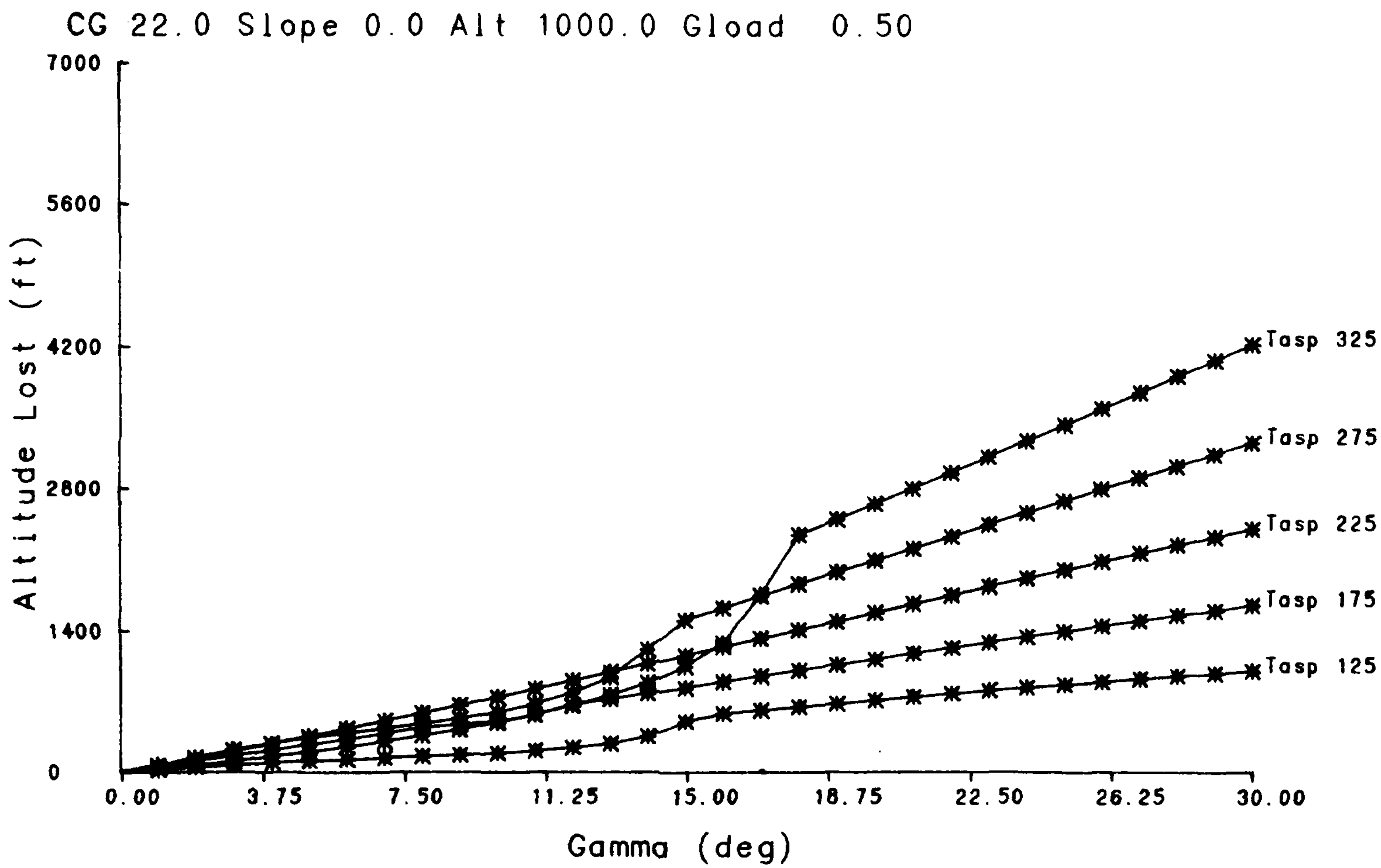


Figure 11. GCASDIVE predicted altitude lost as a function of gamma for: Cg=22, Slope=0, Altitude=1000, & G-load=0.50.

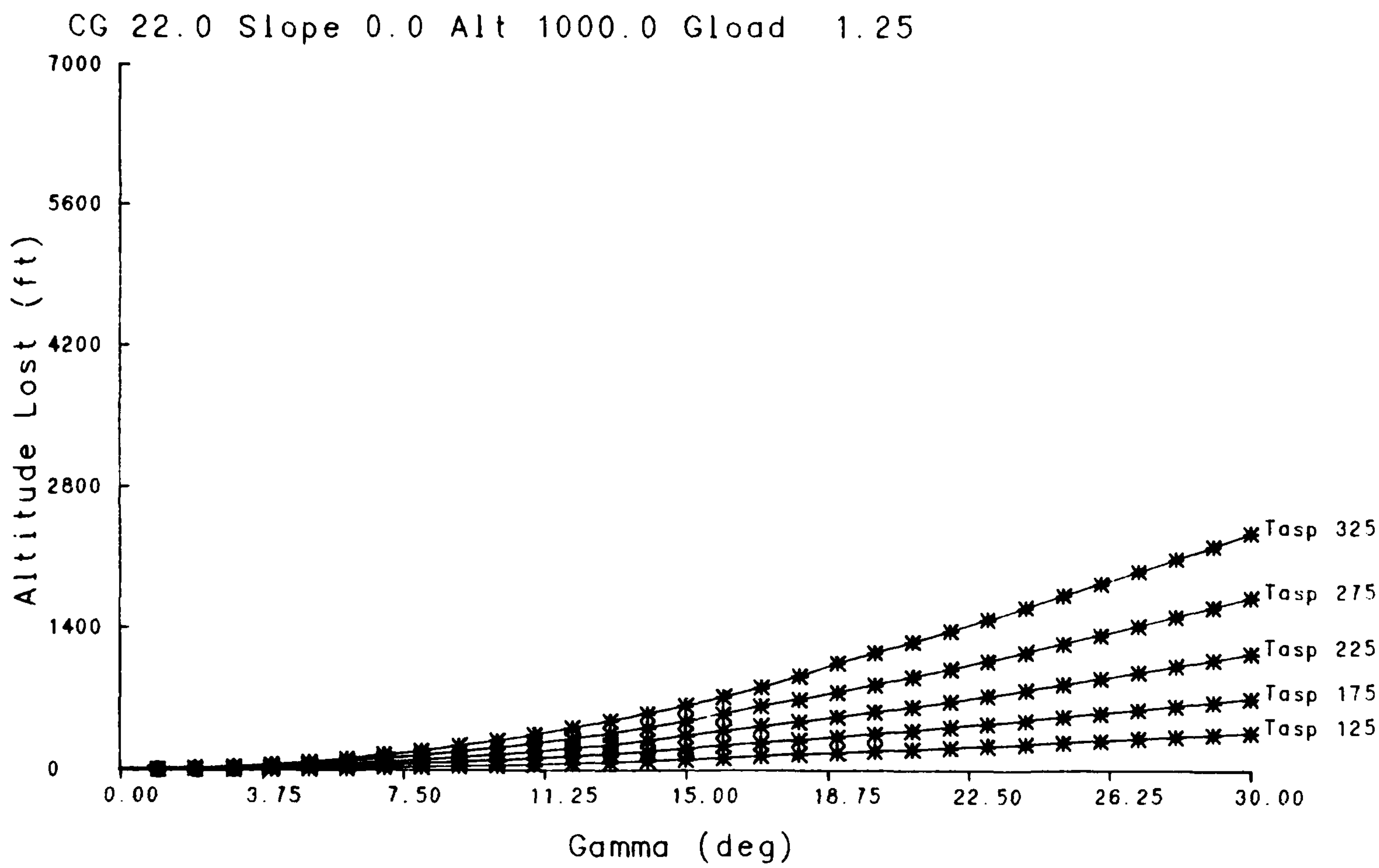


Figure 12. GCASDIVE predicted altitude lost as a function of gamma for: Cg=22, Slope=0, Altitude=1000, & G-load=1.25.

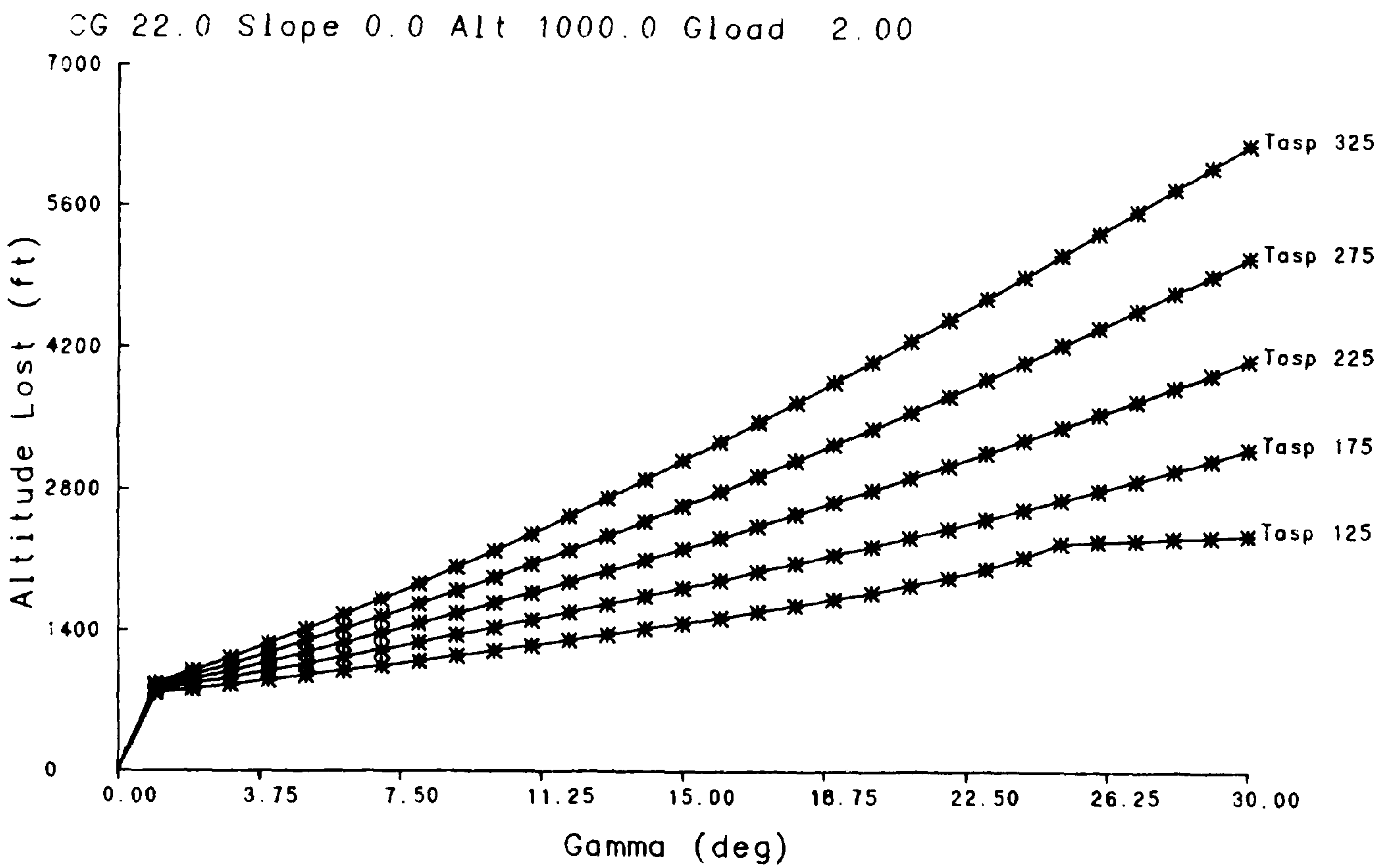


Figure 13. GCASDIVE predicted altitude lost as a function of gamma for: Cg=22, Slope=0, Altitude=1000, & G-load=2.00.

To investigate this anomaly, time-to-target load subroutine graphs using gamma, slope, altitude, and g-load as independent variables were developed. The algorithm used a target g-load of 1.5 g's and then calculated the time to reach that g-load. As expected, an initial g-load of 2.0 resulted in a negative time factor as the target g-load had already been met (Figure 14). Figures 15 and 16 reveal g-loads of 0.5 and 1.25 did result in different predicted times to the target load; however, the effect of airspeed on predicted times was random. It was hypothesized a higher airspeed would result in a faster time-to-target load. Although this was true of the 325 knot true airspeed, the next quickest time curve belonged to the 125 knots, not the 275 knots, as expected. Also, a comparison of Figure 15 with Figure 17 reveals barometric altitude had an effect on time to target. Specifically, the order of the TAS data lines changed with the 125 and 175 knots showing quicker times to the target load than the other airspeeds. These discrepancies contributed to the interactive effect of the g-load factor on the GCASDIVE predicted altitude loss.

To evaluate the effects of terrain elevation (at the time of warning) on the GCASDIVE subroutine, a comparison of Figures 12, 18, and 19 was required. These figures represent terrain elevations of 1000, 10,000, and 19,000, respectively. The comparisons between the figures reveal there was no effect on predicted altitude loss due to terrain elevation. To evaluate the effects of slope on GCASDIVE, Figures 12, 20, and 21 were compared. These figures represent slope conditions of 0, 6, and 12 degrees. No slope effects were observed.

To further investigate the reason slope had no effect on predicted altitude loss, predicted altitude lost graphs were plotted as a function of terrain slope (DCAEXTRP) for airspeed (125 & 225 knots), slope (0, 7, & 14 degrees), and gamma (0-30 degrees). Figures 22 & 23 indicate increases in predicted altitude loss as both airspeed and gamma increased, as expected. No effect could be attributed to slope. The effect was so minimal that the plotter literally typed over the slope identifiers for each data line, as evidenced by the superimposing of the numerals 0, 7, and 14. Based on this analysis, it became apparent the algorithm failed to accurately account for the effects of slope.

GCASROLL

The GCASROLL predicted altitude lost graphs used pressure altitude (1000, 10,000, 19,000); gamma (-5, -10, -20, -30); airspeed (125, 175, 225, 275, 325); and roll (0-90) as independent variables. An inspection of Figure 25 indicates both airspeed and roll caused increases in predicted altitude lost, as expected. However, the effect of roll began at 5 degrees and stabilized at a roll condition of 45 degrees. These are the limits imposed by the algorithm. A comparison of Figures 24 and 25 shows that as gamma increased so did the predicted altitude lost. By reviewing Figures 24 and 26 in a similar fashion, we find pressure altitude had no effect on the predicted altitude loss. A review of the remaining graphs (not included in this report) paralleled these findings. In summary, gamma, roll, and airspeed all had the expected effects on predicted altitude loss for the GCASROLL sub-algorithm.

Discussion

Phase I revealed several problem areas and concerns for the Cubic GCAS algorithm. These problems were: (1) The effects of temperature were never directly considered by the algorithm. (2) The algorithm assumed the effects due to Center of gravity (Cg) were zero. (3) The DCAEXTRP effects of slope used in the GCASDIVE subroutine were minimal. (4) The time-to-target load plots indicated a random prediction of times relative to the aircraft airspeed. Additionally, the algorithm limited the target load to 1.5 g; whereas, the operational limit of the KC-135 is 2.0.

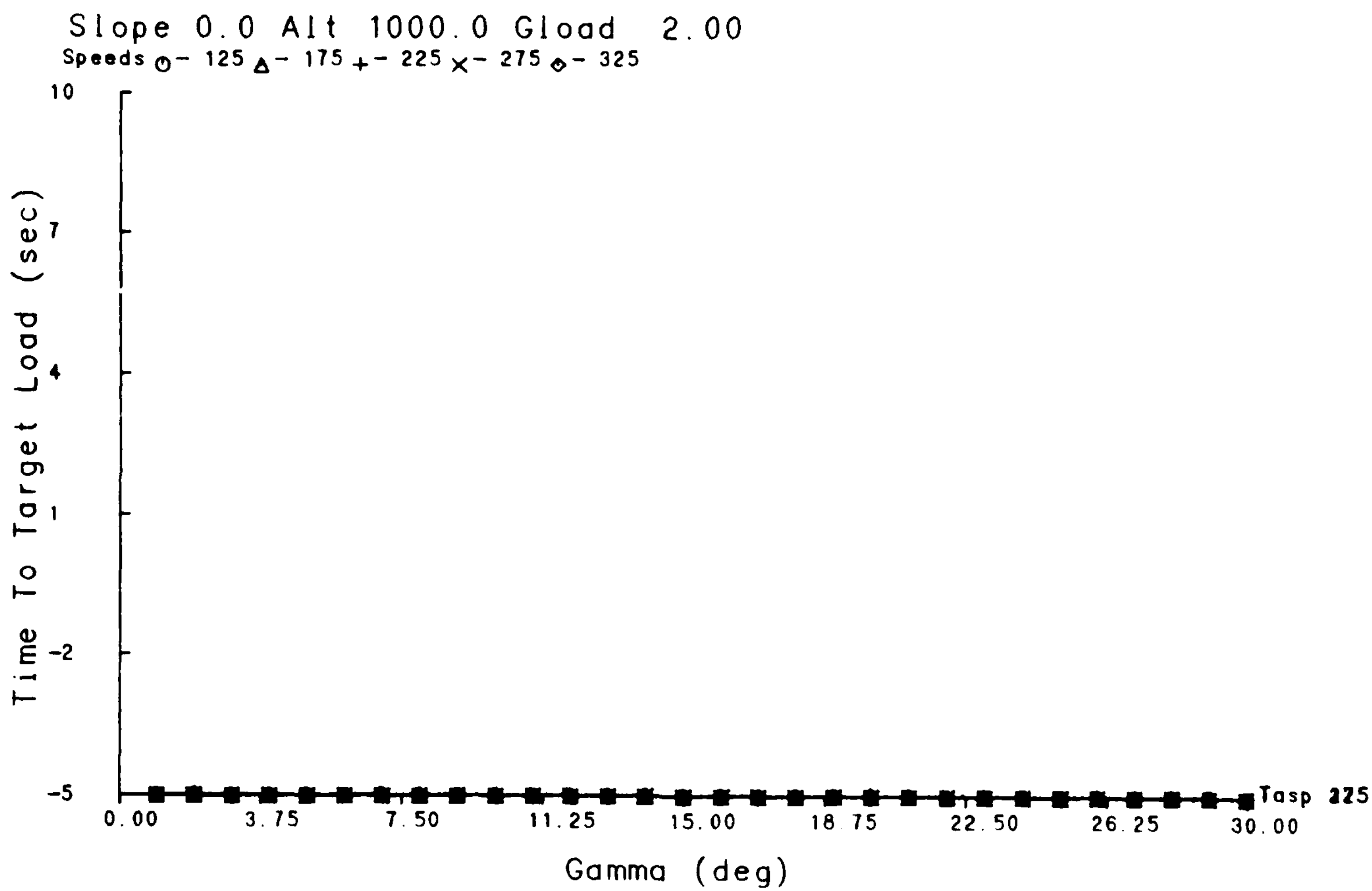


Figure 14. Time-To-Target Load as a function of gamma for: Slope=0, Altitude=1000, & G-load=2.00.

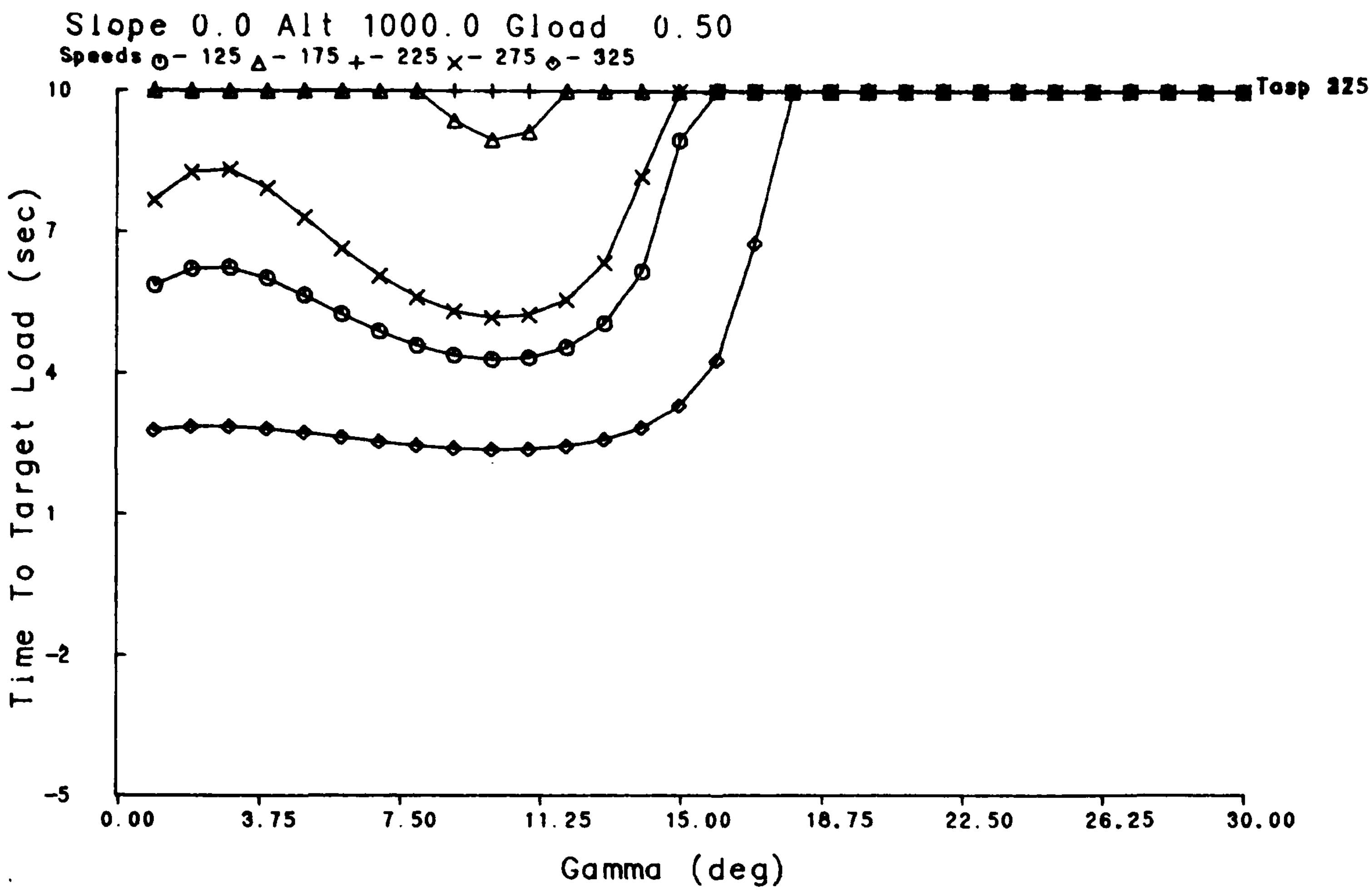


Figure 15. Time-To-Target Load as a function of gamma for: Slope=0, Altitude=1000, & G-load=0.50.

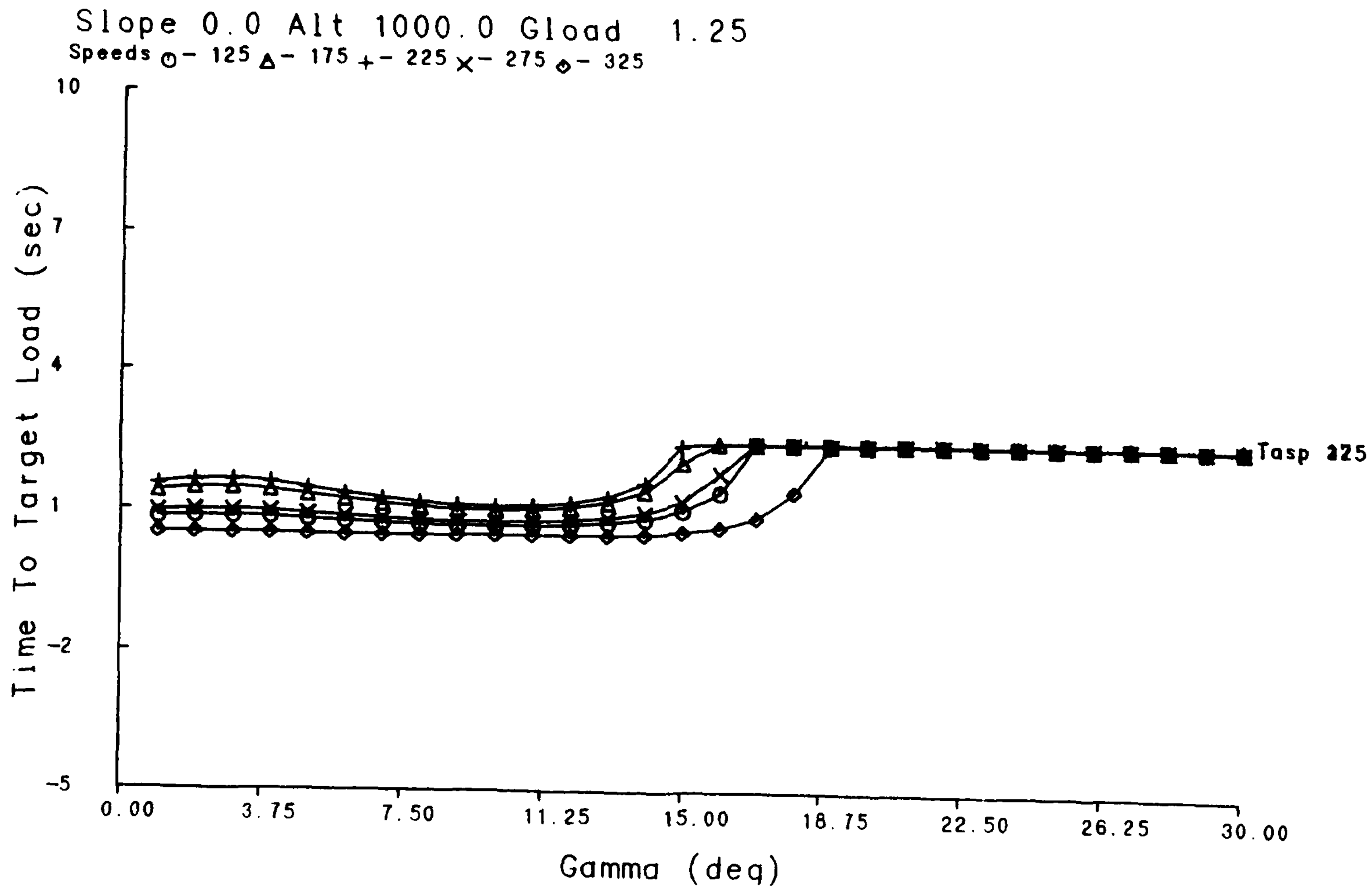


Figure 16. Time-To-Target Load as a function of gamma for: Slope=0, Altitude=1000, & G-load=1.25.

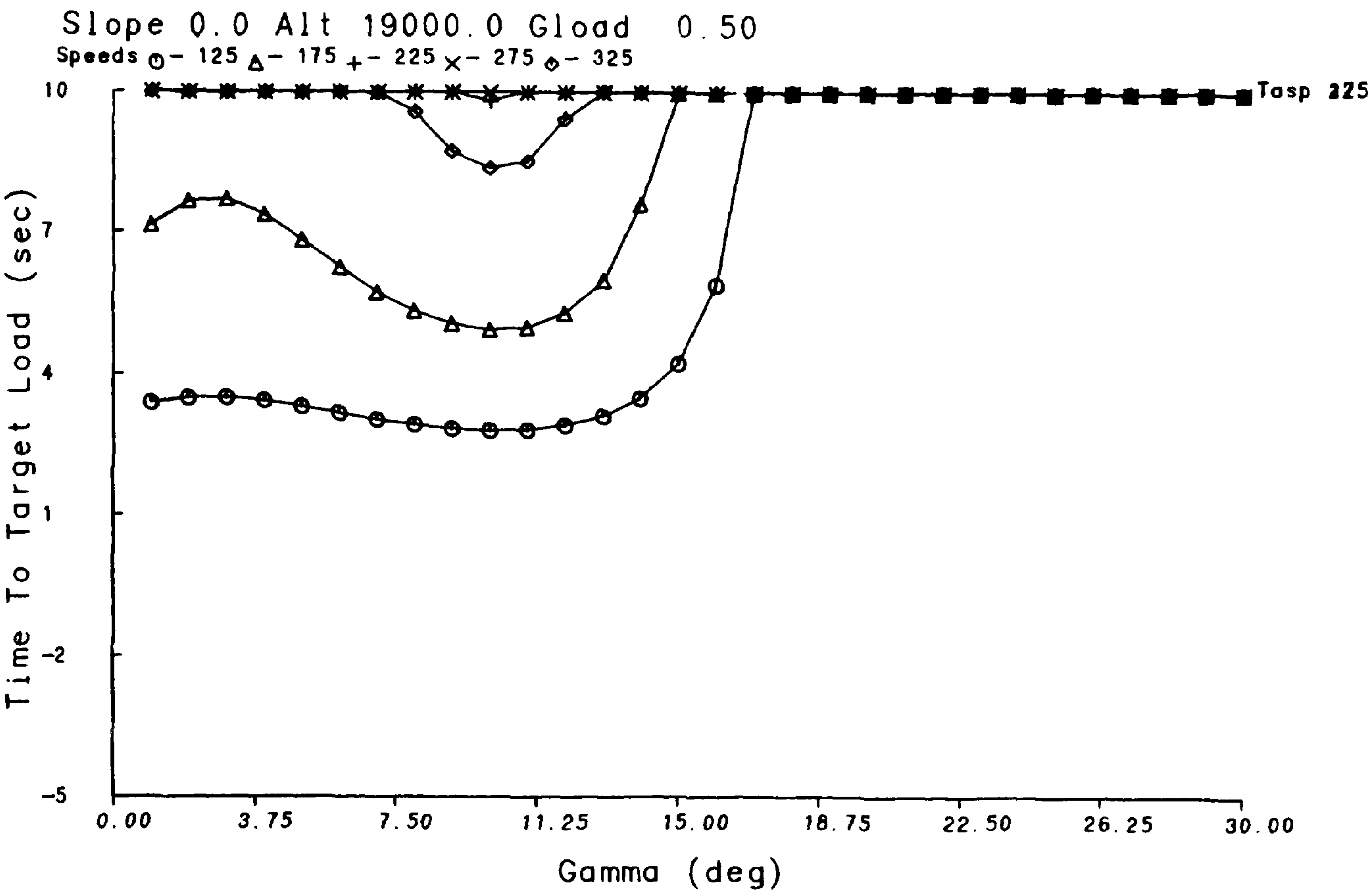


Figure 17. Time-To-Target Load as a function of gamma for: Slope=0, Altitude=19000, & G-load=0.50.

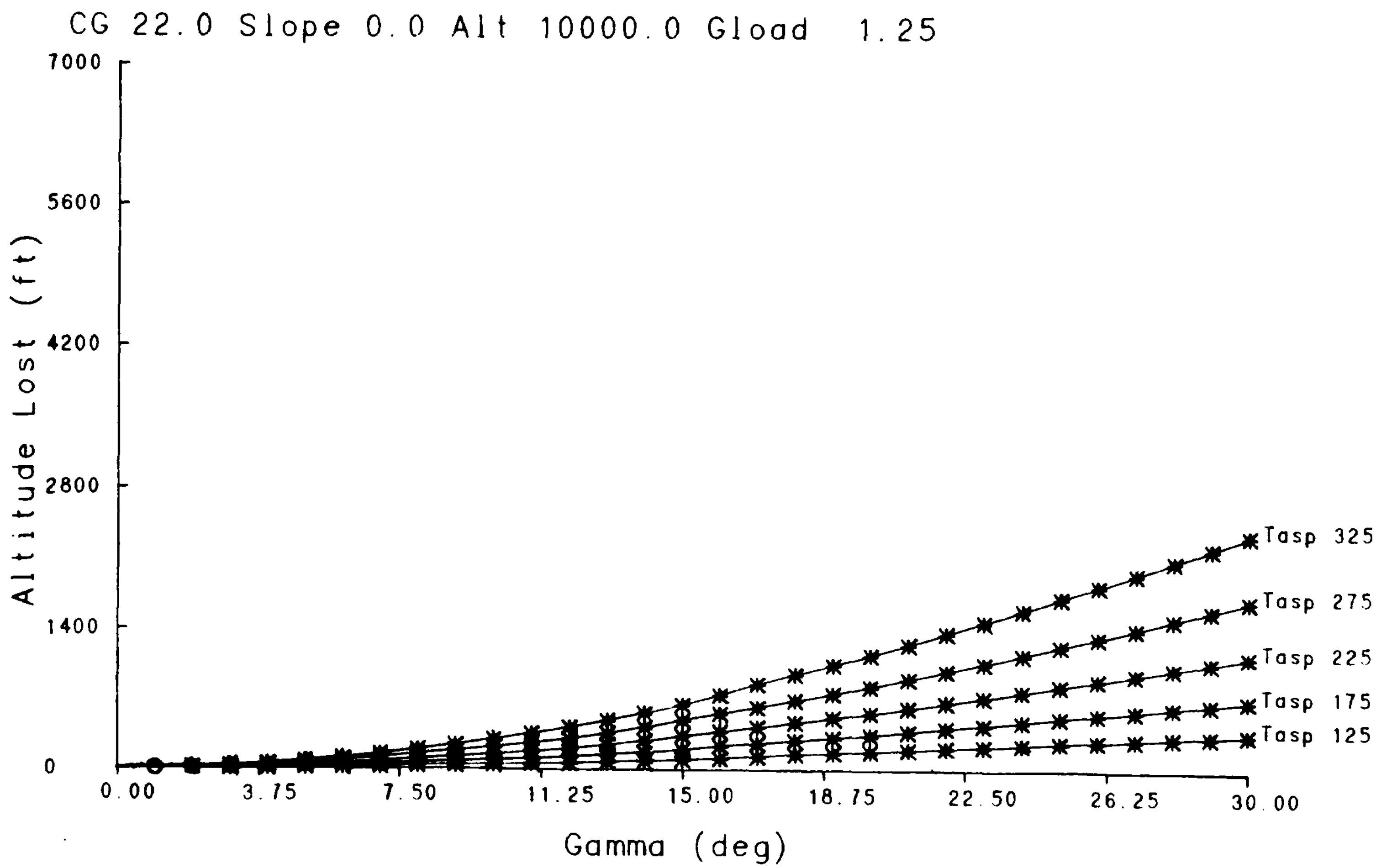


Figure 18. GCASDIVE predicted altitude lost as a function of gamma for: Cg=22, Slope=0, Altitude=10000, & G-load=1.25

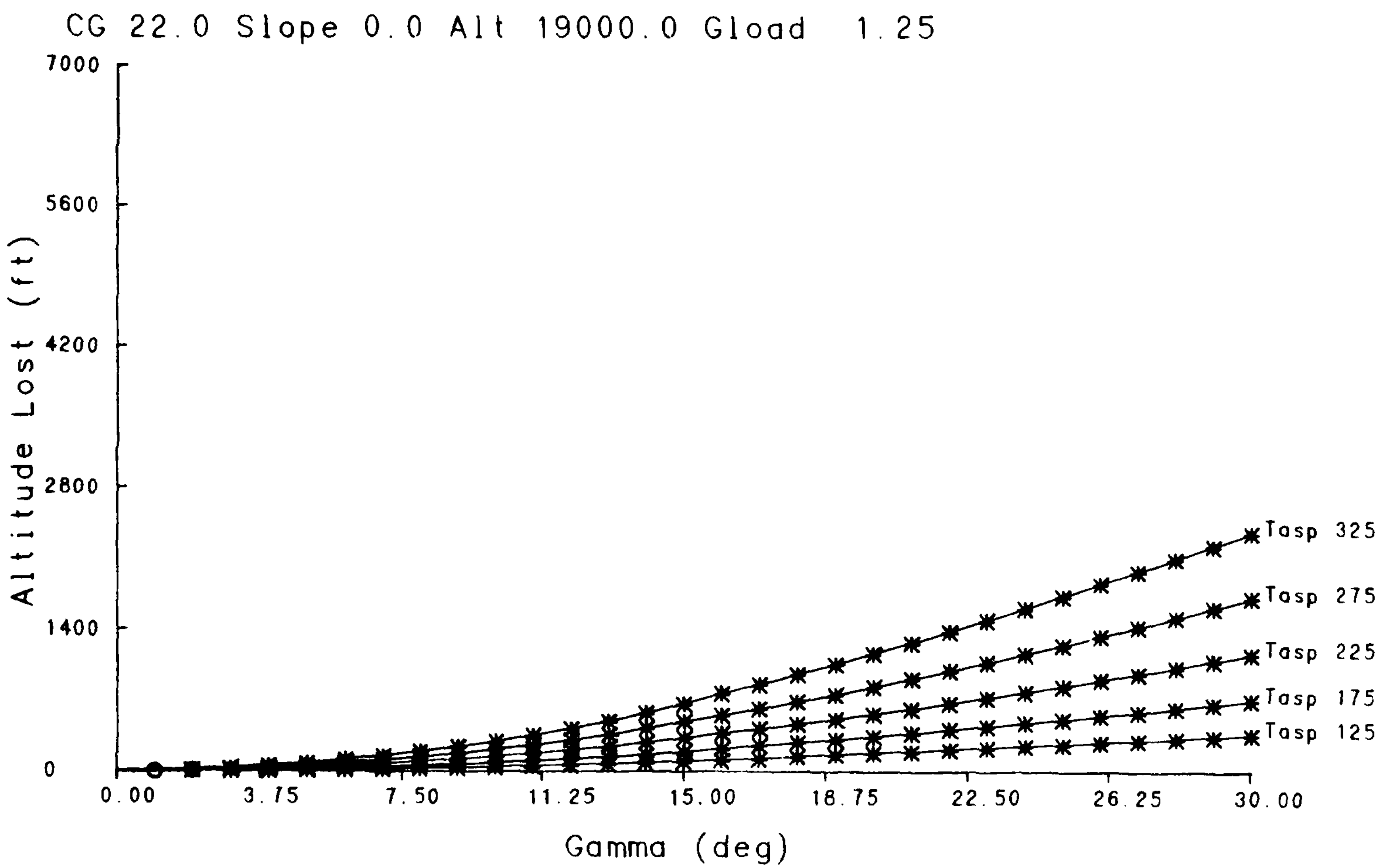


Figure 19. GCASDIVE predicted altitude lost as a function of gamma for: Cg=22, Slope=0, Altitude=19000, & G-load=1.25

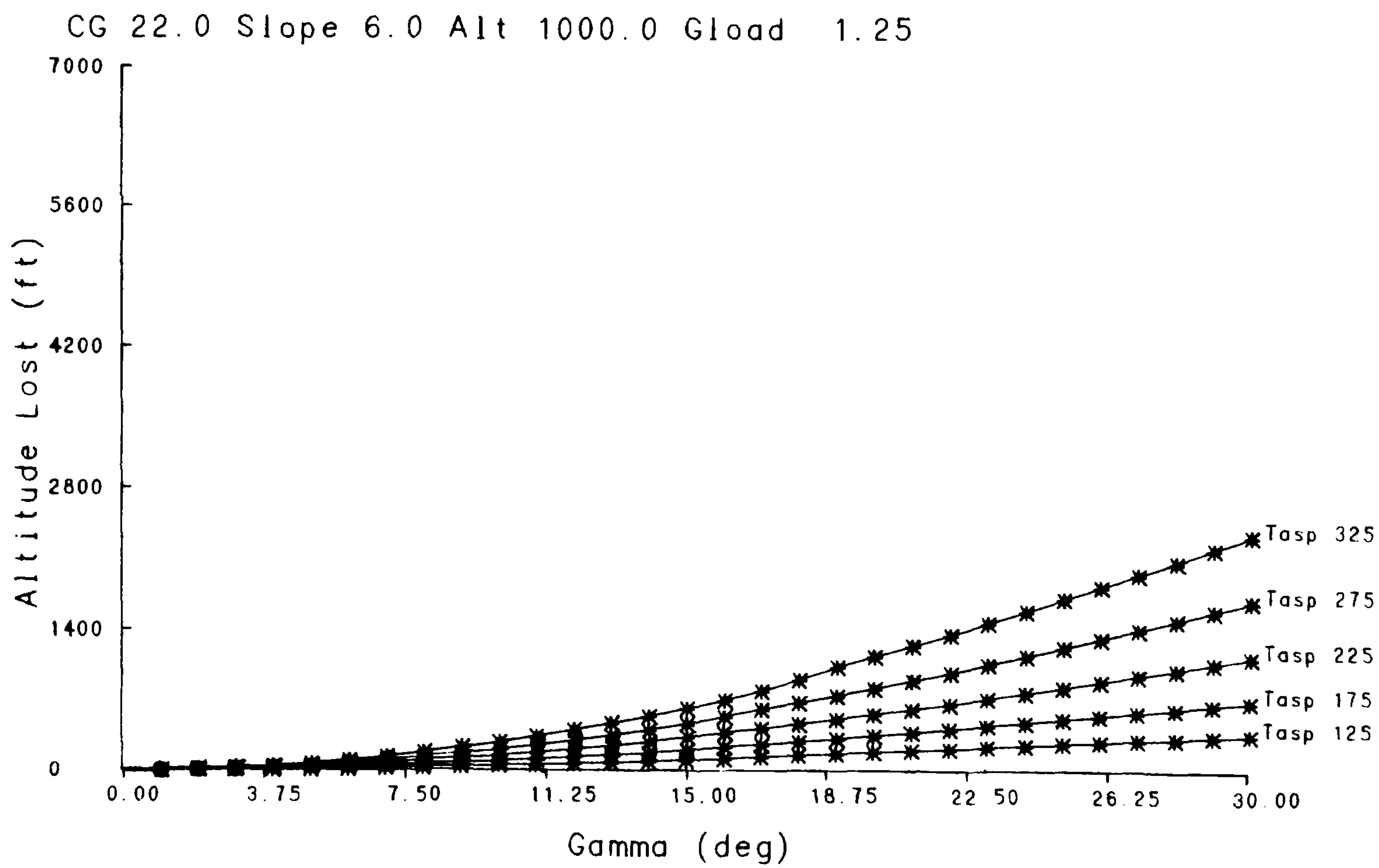


Figure 20. GCASDIVE predicted altitude lost as a function of gamma for: Cg=22, Slope=6, Altitude=1000, & G-load=1.25

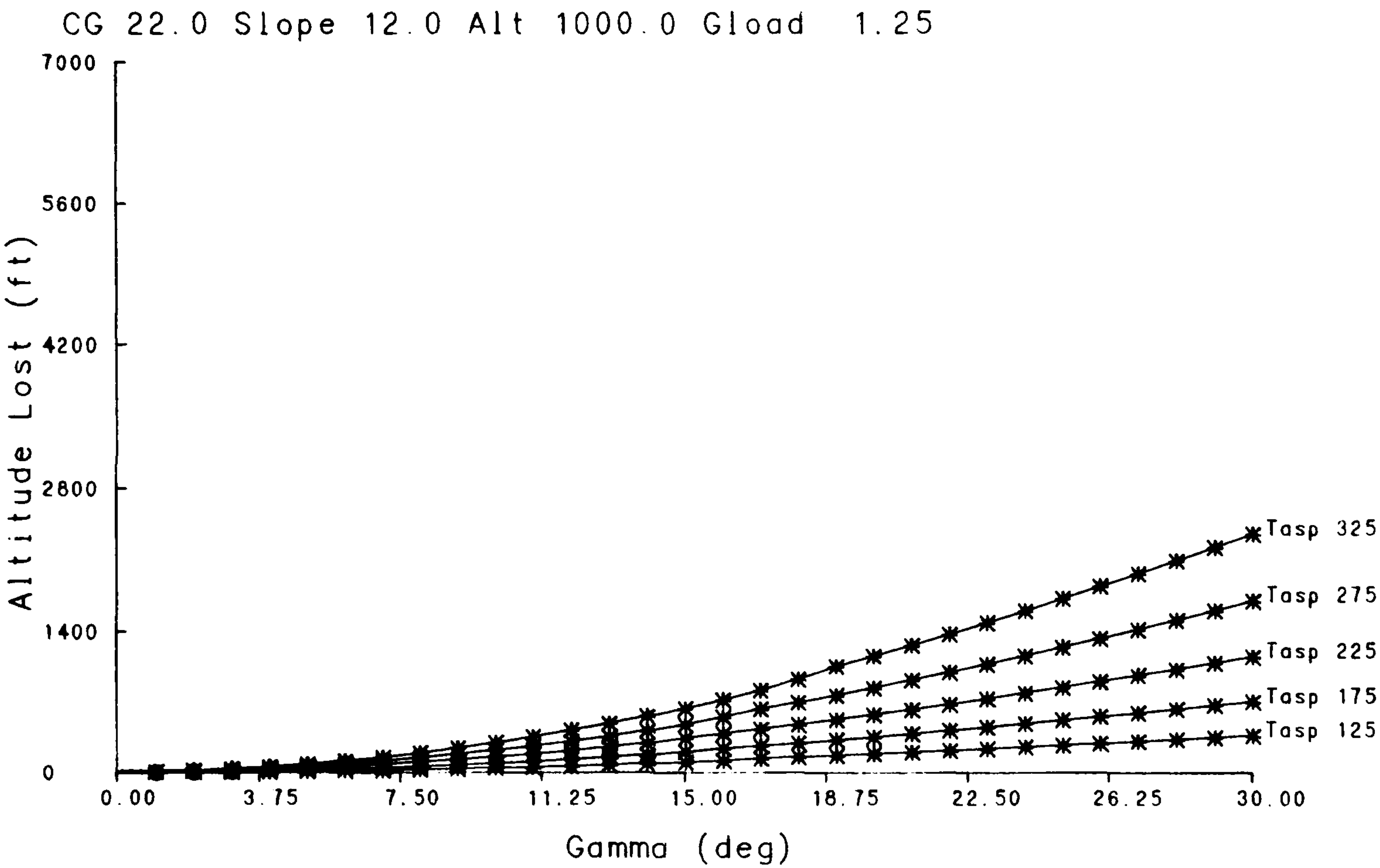


Figure 21. GCASDIVE predicted altitude lost as a function of gamma for: Cg=22, Slope12, Altitude=1000, & G-load=1.25

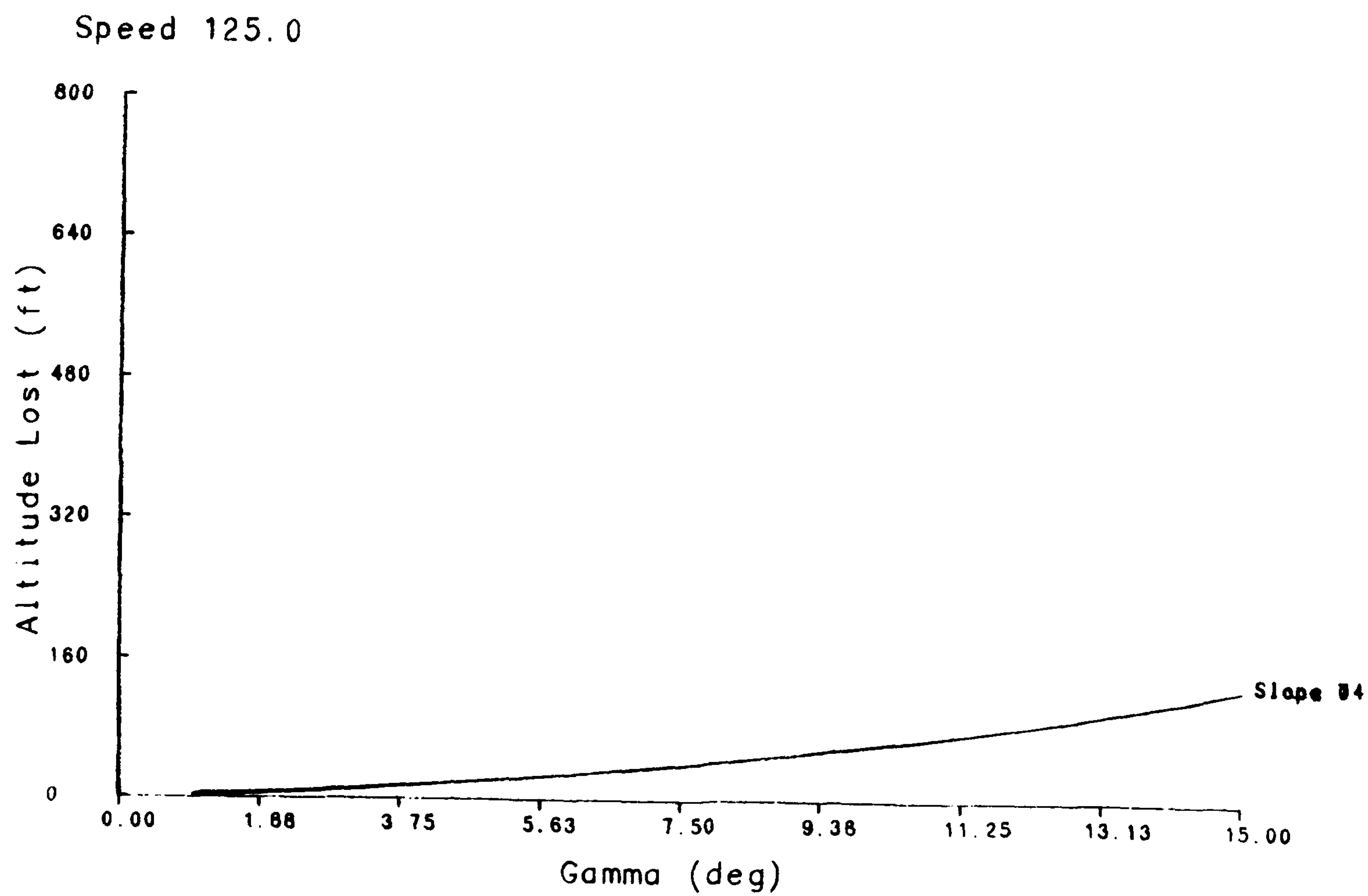


Figure 22. DCAEXTRP predicted altitude lost as a function of gamma: Airspeed=125.

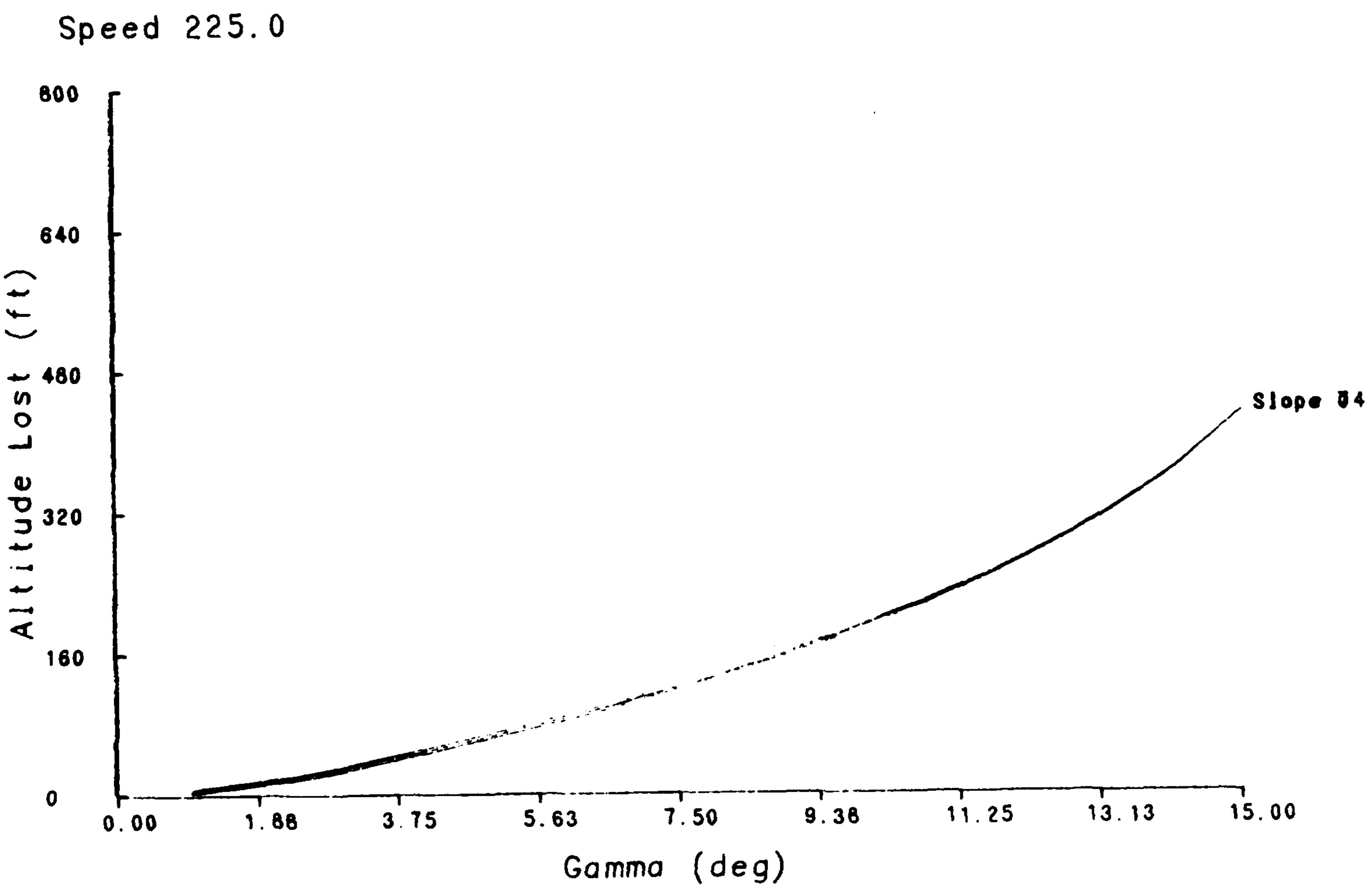


Figure 23. DCAEXTRP predicted altitude lost as a function of gamma: Airspeed=225.

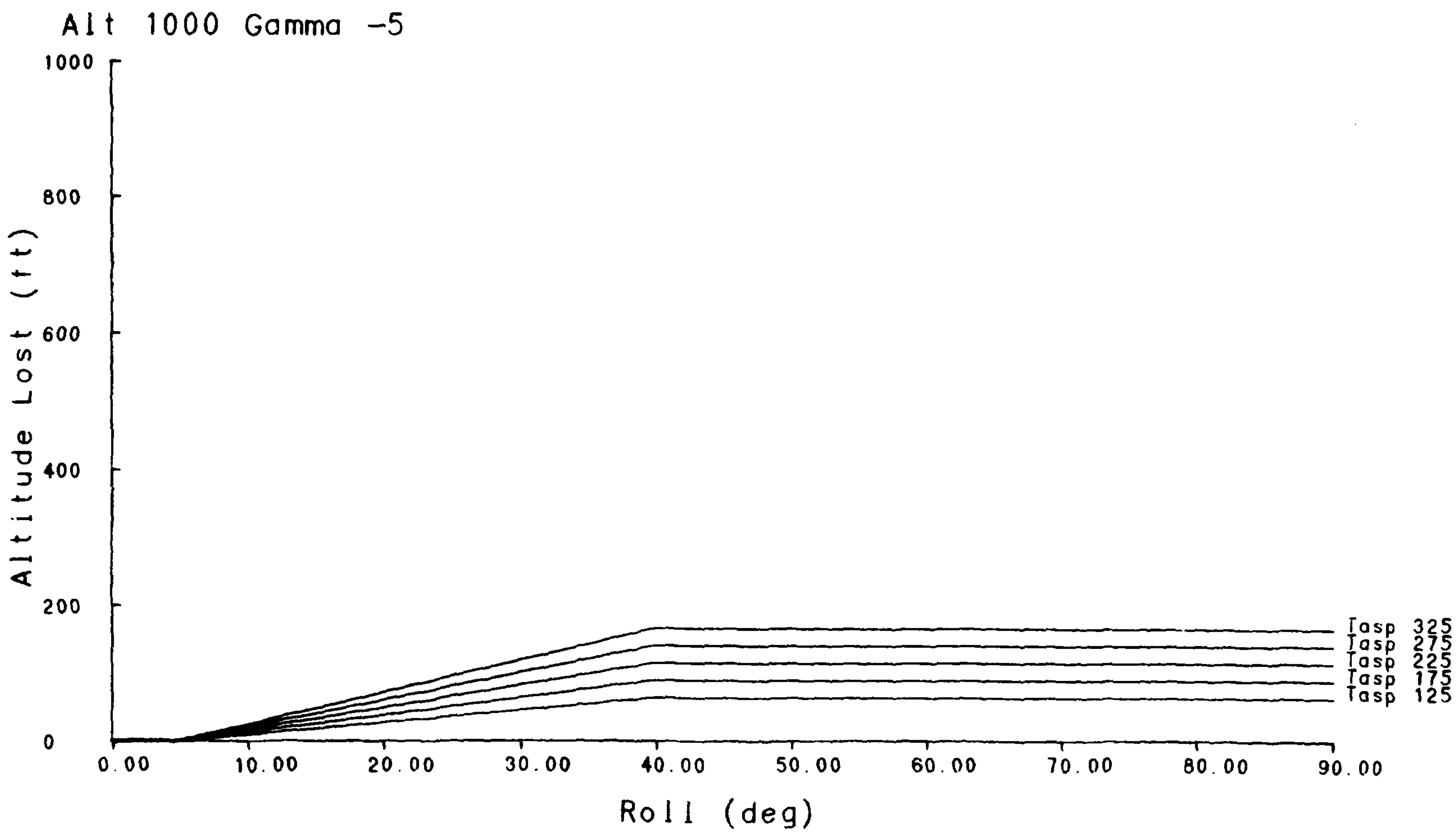


Figure 24. GCASROLL predicted altitude lost as a function of roll: Altitude =1000 & Gamma=-5.

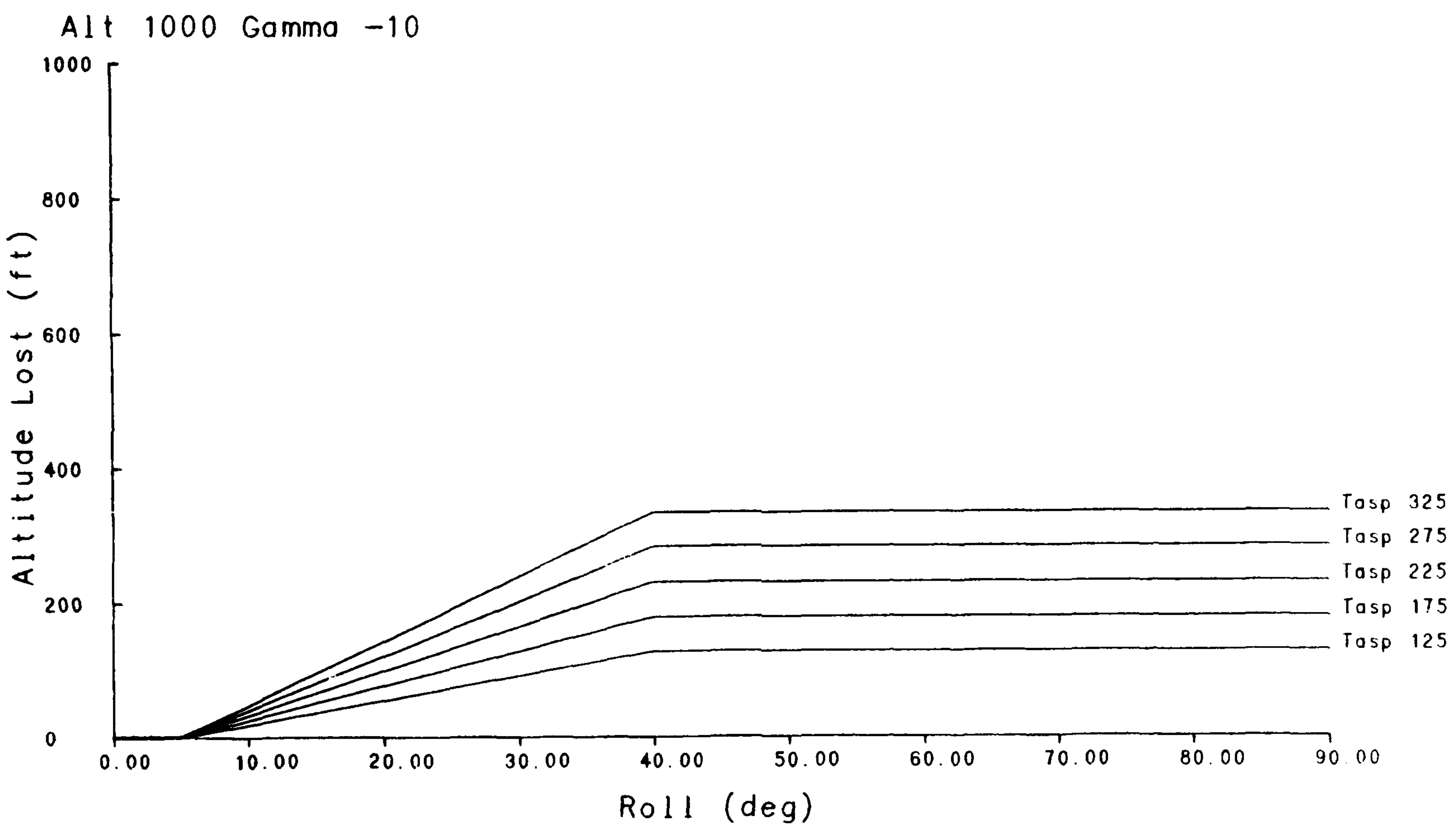


Figure 25. GCASROLL predicted altitude lost as a function of roll: Altitude =1000 & Gamma=-10.

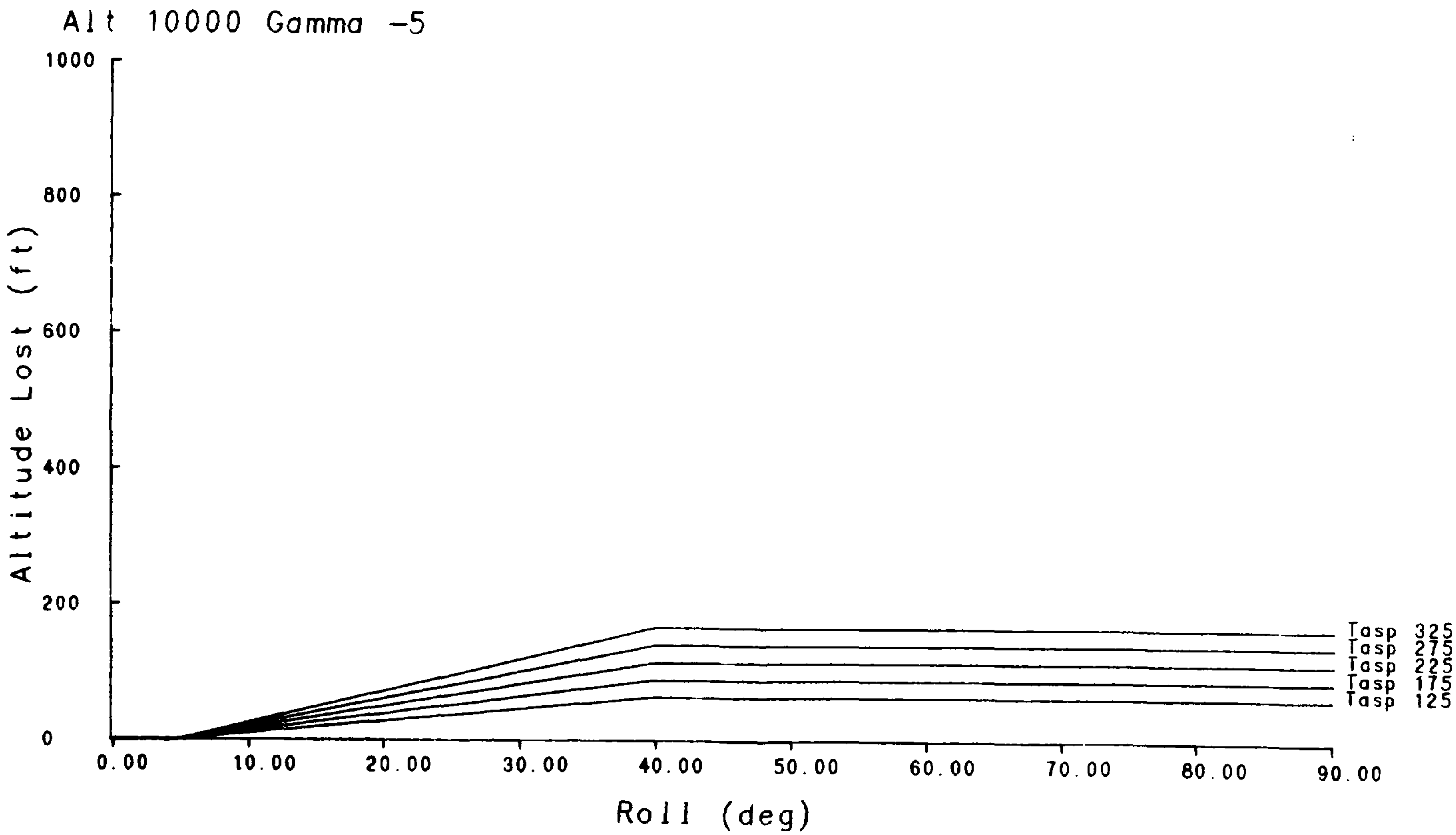


Figure 26. GCASROLL predicted altitude lost as a function of roll: Altitude =10000 & Gamma=-5.

According to the KC-135 performance manual, T.O. 1C-135(K)R-1-1, temperature directly affects engine performance (p. 1A2-2), takeoff and climbout performance (p. 1A3-5), climb performance (p. 1A4-3), descent performance (p. 1A8-2), and approach and landing performance (p. 1A9-4). Given temperature affects the aircraft during the critical phases of flight most prone to CFIT accidents and that none of the subroutines uses temperature as an input, we recommended the temperature variable be considered and either directly or indirectly incorporated into the algorithm.

In a similar fashion, gross weight affects takeoff and climbout performance (p. 1A3-5), descent performance (p. 1A8-2), and approach and landing performance (p. 1A9-4). Since Cg accounts for gross weight in addition to the aircraft center of moment, the need for the algorithm to detect and account for Cg effects is inherently more important. By accounting for the effects of Cg, the algorithm could better predict the expected altitude loss and, therefore, reduce the variability of its prediction.

As seen in Figures 22 & 23, the DCAEXTRP predicted altitude loss due to the effects of terrain slope was essentially zero. This poses a potential problem. If the algorithm is continually calculating for a no slope condition, then a controlled flight into terrain accident would be much more likely to occur under conditions of increasing slope. The fact the algorithm fails to account for the effects of slope renders the system relatively useless given the terrain of the earth is generally sloping to one degree or another.

Initial indications of the fourth problem area suggested the variability in the prediction of the time-to-target across true airspeeds resulted in an interaction of G-load with pressure altitude. Figures 15-17 indicate this unexpected pattern of results for time-to-target load. Accordingly, the predicted altitude loss for the GCASDIVE subroutine varied in a similar manner for the different g-load conditions. Since Figures 15-17 revealed an unexpected pattern of results, the time-to-target load subroutine needed to be reevaluated by Cubic.

Phase I provided an initial look at how the algorithm was designed and how it should work. After breaking the algorithm down into its main subroutines, we were able to obtain an idea of how well the algorithm would predict and under what conditions or situations there may be a problem. The problem areas listed above were then forwarded to the Cubic Corporation to allow them to incorporate the changes they deemed necessary into their algorithm prior to the Phase II evaluation.

Prior to Phase II, Cubic only addressed one of the four concerns found during Phase I. Specifically, Cubic accounted for the effects of temperature through the use of indicated, as well as true airspeed. Cubic stated the problem areas concerning the DCAEXTRP effects of slope and the time-to-target load plots were "OK" and did not need revision. Cubic also stated they did not have sufficient information to incorporate Cg into their algorithm at that time. Given Cubic's reply and SPO direction, the Phase II portion of our evaluation was performed.

PHASE II

The objective of the Phase II evaluation was to determine the GCAS algorithm response characteristics as a function of five independent variables: Terrain slope, terrain elevation, indicated airspeed, aircraft roll angle, and flight path angle (gamma). The KC-135 simulator was placed in a specific configuration based on the independent variables above. Upon release of the simulator, a simple robot pilot model attempted to stabilize the simulator at one "G" while maintaining the given run conditions until a pull-up warning was initiated. Following a predetermined delay, based on the algorithm's calculations for predicted pilot reaction time, the pull-up maneuver was then performed by the pilot model based on the following criteria: Roll and pull simultaneously to a maximum of three Gs. This condition was maintained until the flight path angle of the aircraft became greater than that of the terrain.

Phase II was run in two separate parts using the robot pilot model. Each part followed the described methodology below. Part 1 was the initial analysis performed on the revised Cubic algorithm from Phase I. Cubic then responded to the problems areas found in Part 1. Part 2 was an evaluation of the revised Cubic algorithm, which included the changes Cubic deemed necessary to correct the deficiencies found during Phase II - Part 1. Each part will be discussed in detail.

Method

Apparatus

Facility. The study was conducted at the Crew Station Evaluation Facility (CSEF), which is a U.S. Air Force simulation facility that belongs to the Aeronautical Systems Division (ASD) of Air Force Systems Command. CSEF government personnel are assigned by the Crew Systems Division (ASD/ENEC). The facility is used to perform human engineering experiments in support of a variety of System Program Offices.

Simulator. The KC-135 simulator, shown in Figures 27 and 28, rested on a three degree-of-freedom motion platform, and included such major components as the control loading assemblies, seats, yokes, and visual windows. The simulator was equipped with two wide angle collimating windows that provided a panoramic outside scene capable of supporting the CSEF Night Visual System (NVS). A Digital Equipment Corporation (DEC) PDP 11/35 computer used one of a number of databases to generate sets of lights, simulating various night visual scenes, for the NVS. This provided the pilot with a visual capability used in Phases III and IV of our study. The KC-135 simulator contained all the instrumentation found in the actual cockpit for both the pilot and copilot positions. The software package contained all flight, engine, atmosphere, weights and balances modules; a dictionary of all KC-135 data variables; and several other specific commons and data pools for the KC-135C model aircraft.

Computer Complex. The simulator was connected to a series of large and small computer systems. This computer complex included five Gould series 32/7780, one Gould concept 32/8780, two PDP 11/34, three PDP 11/35, and several Silicon Graphics Iris Work Stations.

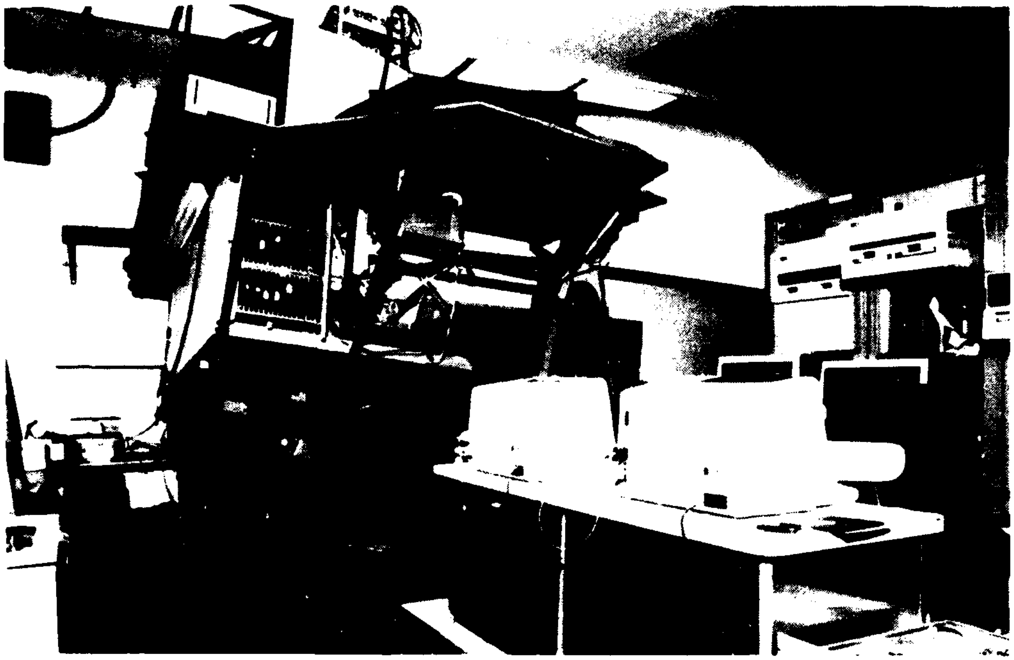


Figure 27. Picture of KC-135 simulator exterior.

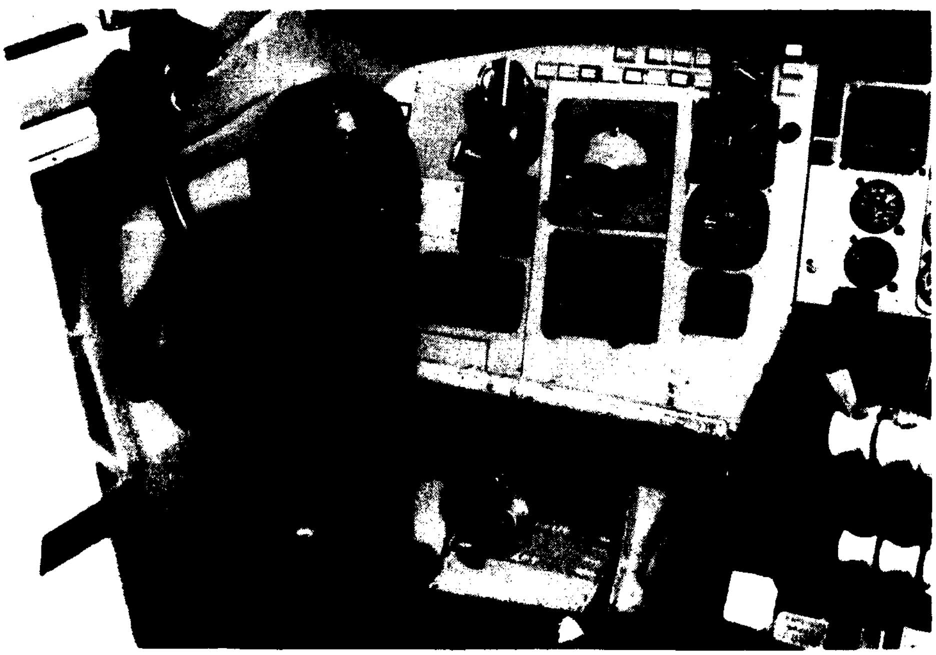


Figure 28. Picture of KC-135 simulator cockpit .

Design

The objective of the Phase II evaluation was to determine the GCAS algorithm response characteristics as a function of five independent variables: Terrain slope, terrain elevation, indicated airspeed, aircraft roll angle, and flight path angle (gamma). Terrain slope was the slope of the terrain at warning initiation; whereas, terrain elevation was the height of the terrain (MSL) at the beginning of each simulation trial. The remaining three variables were recorded at the time of warning initiation. Table 1 lists the different levels for each of the independent variables.

Table 1. Phase II independent variables.

ROLL	GAMMA	IAS	SLOPE	ELEVATION
0	-5	225	0	1000
15	-10	275	7	10000
30	-15	325	14	
45	-20			

The actual condition of the aircraft and the predicted altitude loss by each of the subroutines were recorded for each of the robot runs. Three dependent measures of interest were also recorded for subsequent data analysis. These were maximum g's, minimum clearance altitude, and total altitude lost. Maximum g's represented the highest instantaneous g-force placed on the aircraft, and acted as our criterion for accepting or rejecting a given robot run. If a run exceeded 3.0 g's, then the run was discarded and a new run performed. This value was chosen as it represented the structural limit of the aircraft (3.0).

Total altitude lost allowed the comparison of the actual total altitude loss with the algorithm's predicted total altitude loss. The minimum clearance altitude, defined as the minimum distance between the aircraft and the ground (feet-AGL) during the aircraft's recovery, was the primary dependent variable of interest. This variable provided the experimenter with the information needed to determine if the algorithm had provided adequate ground clearance. The overall experimental design was comprised of a single run per condition for a total of 288 trials (4 Roll x 4 Gamma x 3 IAS x 3 Slope x 2 Elevation). All runs were successfully completed.

Procedure

A set-up control interface program developed to simplify user-computer interaction allowed the experimenter to monitor real-time characteristics of the simulator as it flew each configuration. Table 2 presents an example of the computer program page the experimenter used to manipulate a number of variables related to the simulator, the terrain it flew over, and the response characteristics of the pilot model. The actual pilot model was fashioned after the response patterns of two individual operational KC-135 pilots. These data had been gathered through an earlier pilot study.

Table 2. An example of the robot pilot model set-up page.

GCAS ROBOT RUNS

1. TRIAL #	: 115	A. INCREMENT RUN	: ON
2. ROLL ANGLE	: 30.	B. DATA COL	: OFF
3. GAMMA	: -5.		
4. AIR SPEED	: 275.		
5. TERRAIN SLOPE	: 14.		
6. BUFFER ELEV	: 1000.		
7. ALTITUDE	: 5000.		
8. GS	: 2.		

PRESS 'R' TO RUN

Upon releasing the aircraft, the experimenter was presented with a new data page that allowed the monitoring of real time simulator performance characteristics (Table 3). The pilot model attempted to stabilize and maintain the simulator at one G, until the warning signal was initiated. The response delay of the robot pilot model was configured so that the pull-up maneuver was delayed for approximately the same amount of time as that calculated for the pilot response time by the algorithm's PILTRESP subroutine. Rolling out and pulling back were executed simultaneously with a maximum of two and a half G's. The recovery procedure continued until a positive radar altitude rate of climb was established. At run completion, the experimenter could plot the course and the performance characteristics exhibited throughout the pull-up maneuver (Figure 29). This allowed immediate determination of the validity of the run.

Table 3. An example of the data display page available to the experimenter.

GCAS DATA DISPLAY PAGE

GAMMA	-5.9	PITCH	-4.3	ALT	5000
ROLL	29.7	AOA	1.6	RALT	3922
IAS	261	G'S	.9	VVI	-2944
				WARN:	(NO WARNING)

KC135 STATUS	INITIAL CONDITIONS		DATA COLLECTION
(FLYING)	ROLL	30	RUN # : 115
	GAMMA	-5	DATA : (INACTIVE)
	SPEED	275	
	SLOPE	14	
	ALTITUDE	5000	

PRESS ATTENTION TO EXIT DATA

Figure 29 displays the initial run conditions at the top of the page as well as in the first six lines along the right side of the graph. The next four lines along the side of the graph were the algorithm's predicted altitude loss for each of the subroutines,

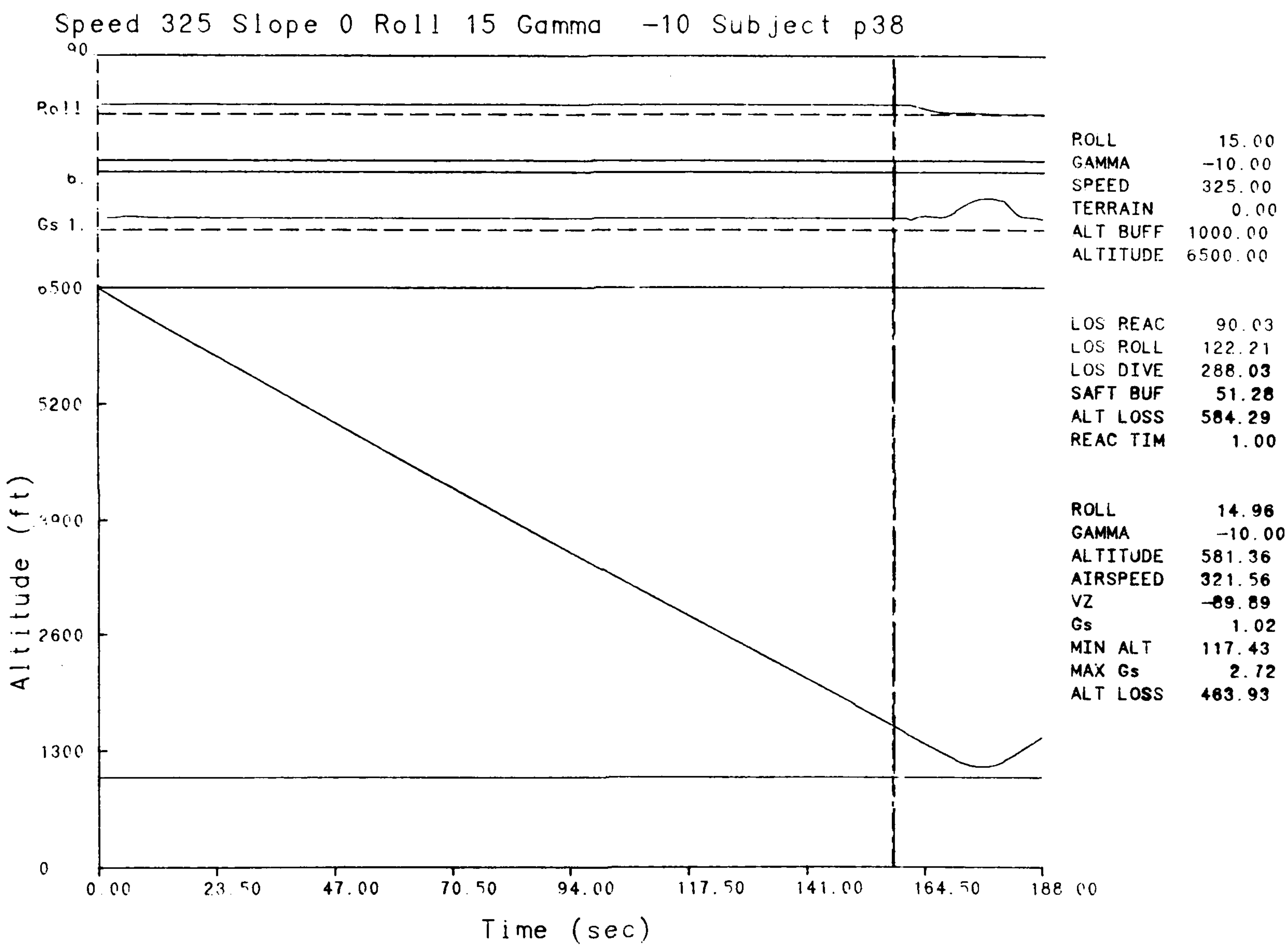


Figure 29. Typical output plot available for "quick look" evaluations.

GCASALRT, GCASROLL, and GCASDIVE, in addition to the algorithm's calculated safety buffer. These were then summed to obtain the total predicted altitude loss, ALT LOSS. The reaction time listed is that used by the algorithm. The roll, gamma, altitude, airspeed, and vertical velocity (VZ) found in the third group of variables, were the actual conditions of the aircraft simulator at warning initiation. Maximum G's (MAX Gs) and actual total altitude loss (ALT LOSS) were the maximum values obtained during aircraft recovery. Minimum clearance (MIN ALT) represents the minimum distance between the aircraft and the terrain that occurred during the GCAS recovery. The roll line and Gs line represent the real time roll and g-load values of the aircraft during its flight. The x-axis is the total running time since the run began. The y-axis is the altitude of the aircraft in feet (MSL). The flight of the aircraft is represented by the curved upper line beginning at the maximum value of the y-axis. The ground level is represented by the straight line that begins at a terrain elevation of 1000 feet.

Several hypotheses were generated based on earlier discussions with pilots and previous GCAS work (Hassoun, Ward, Barnaba, & McCarthy, 1989). It was hypothesized that increases in gamma, roll, airspeed, terrain slope, and terrain elevation would result in increased minimum clearances. This is based on the finding that as downward vertical velocity increased, pilots felt a corresponding increase in minimum clearance would be necessary to provide a safe and comfortable recovery. Gamma and indicated airspeed directly affect downward vertical velocity. Terrain elevation indirectly affects vertical velocity by providing decreased air densities as the elevation or mean sea level increases. The hypothesized roll effect was based on pilot comments that they felt the increased workload, roll recovery in addition to dive recovery, would dictate a desired higher minimum clearance. Increased terrain slope was hypothesized to increase minimum clearance altitudes, as rising terrain would cause additional stress on the pilot and must, therefore, be compensated by higher minimum clearance altitudes.

Part 1 Results

No formal statistical analyzes were performed on the data since only one subject (the robot aircraft) existed. However, the data from all 288 runs were sorted by indicated airspeed, terrain slope, and terrain elevation, and graphed for minimum clearance as a function of flight path angle (gamma) for all the roll angle conditions. A comparison of Figures 30-47 with each other provided the information needed to determine the algorithm's ability to provide adequate minimum clearance.

Terrain Elevation Effects

To determine the effects due to terrain, the 1000-foot terrain elevation had to be compared with the same indicated airspeed and terrain slope graphs for a terrain elevation of 10,000 feet. This required the following comparisons: Figures 30 & 39, Figures 31 & 40, Figures 32 & 41, etc. The result of such comparisons indicated the elevation of the terrain had a direct effect on the minimum clearance altitude of the aircraft. The effect was in the hypothesized direction, minimum clearance increased as terrain elevation increased. The effect also increased more dramatically as the flight path angle of the aircraft increased. Since the effect was constant across graph comparisons and acted to increase the minimum clearance provided, we felt the terrain elevation variable was being adequately considered by the algorithm. Given elevation effects were adequately considered and report brevity is highly desired, further discussion of the graph comparisons will focus on the 1000-foot terrain elevation graphs (Figures 30-38); although, similar comparisons by altitude could be and were made during the actual analysis.

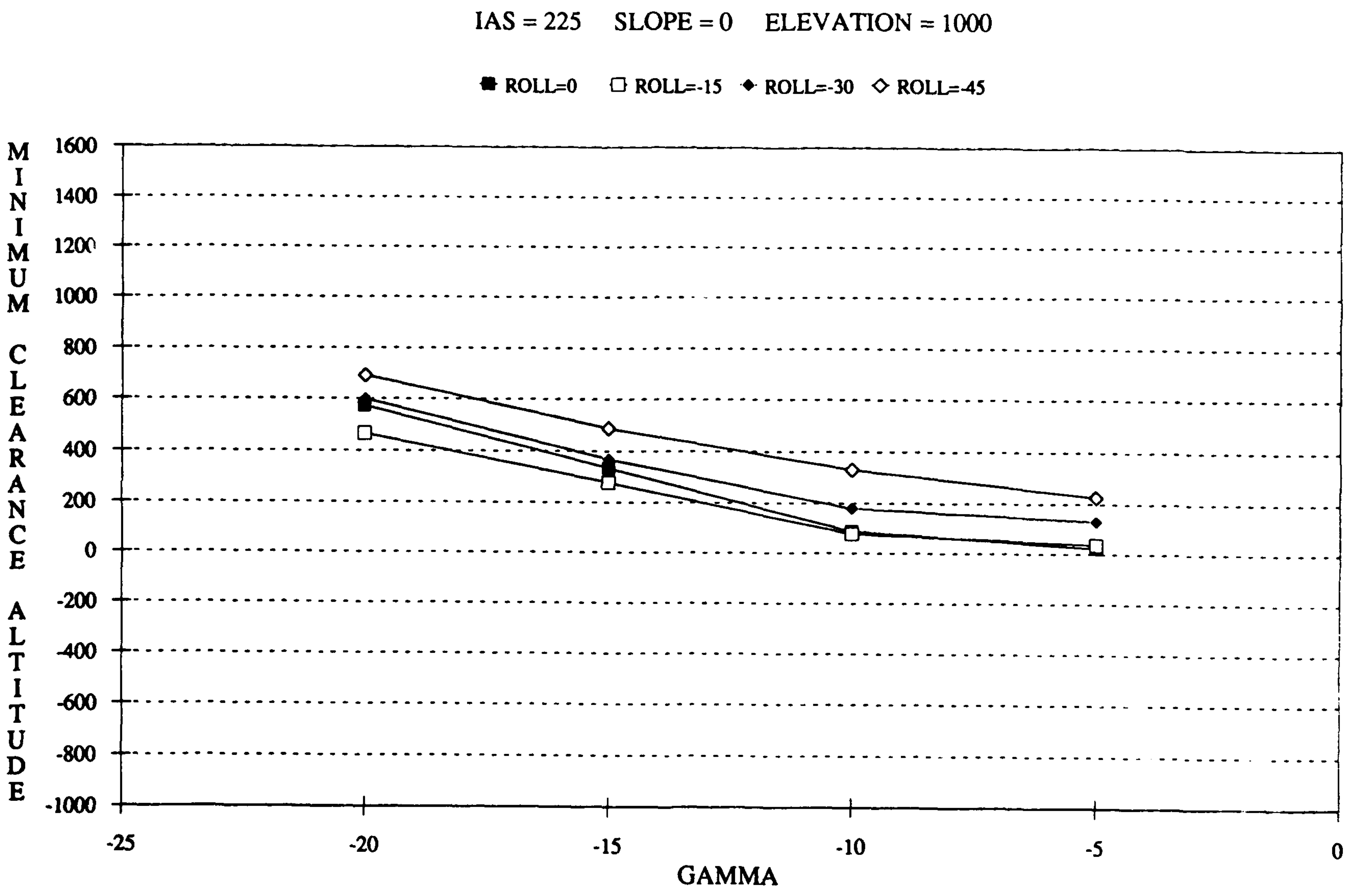


Figure 30. Minimum clearance as a function of gamma for pilot model: IAS=225, Slope=0, & Elevation=1000.

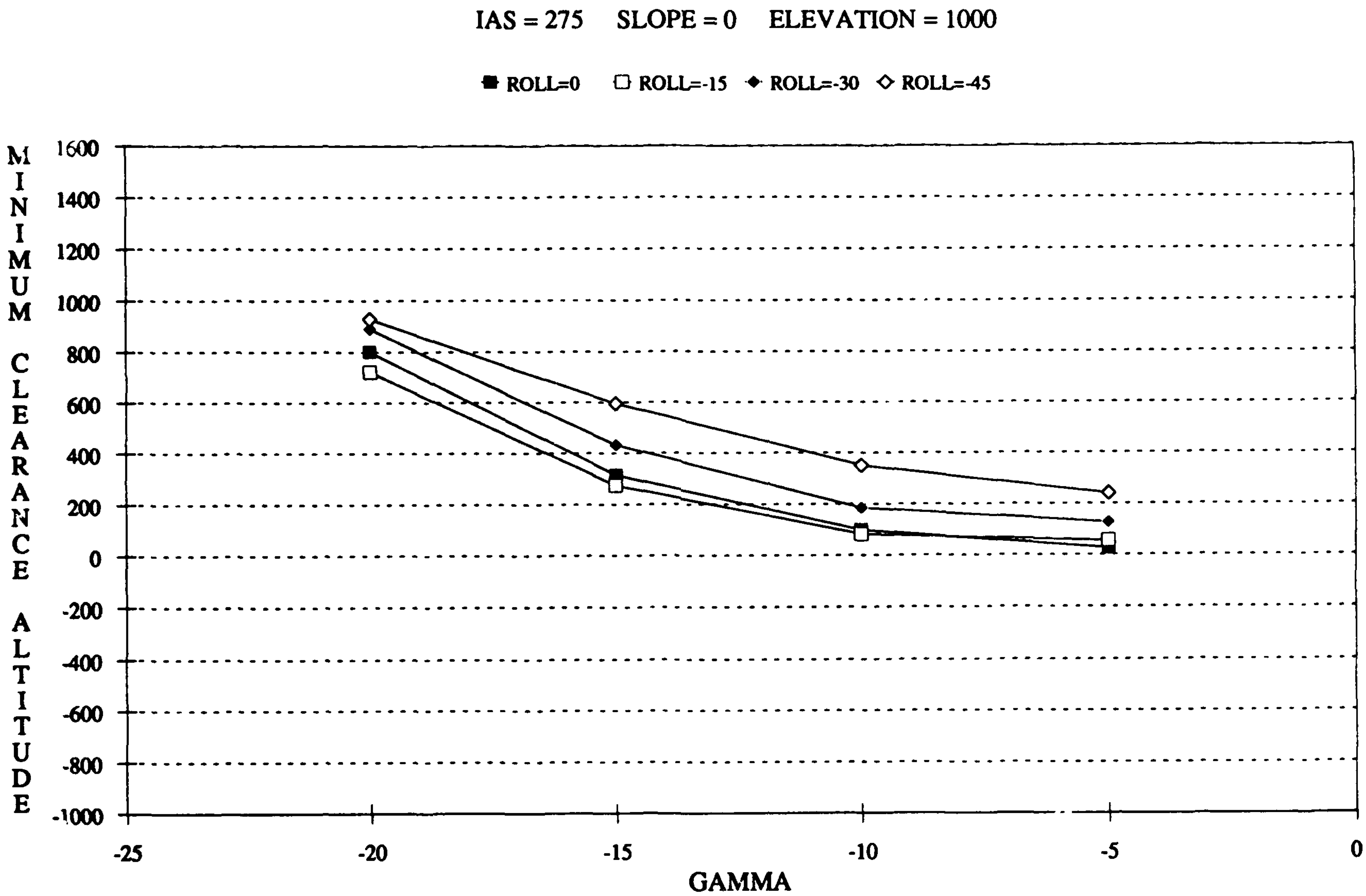


Figure 31. Minimum clearance as a function of gamma for pilot model: IAS=275, Slope=0, & Elevation=1000.

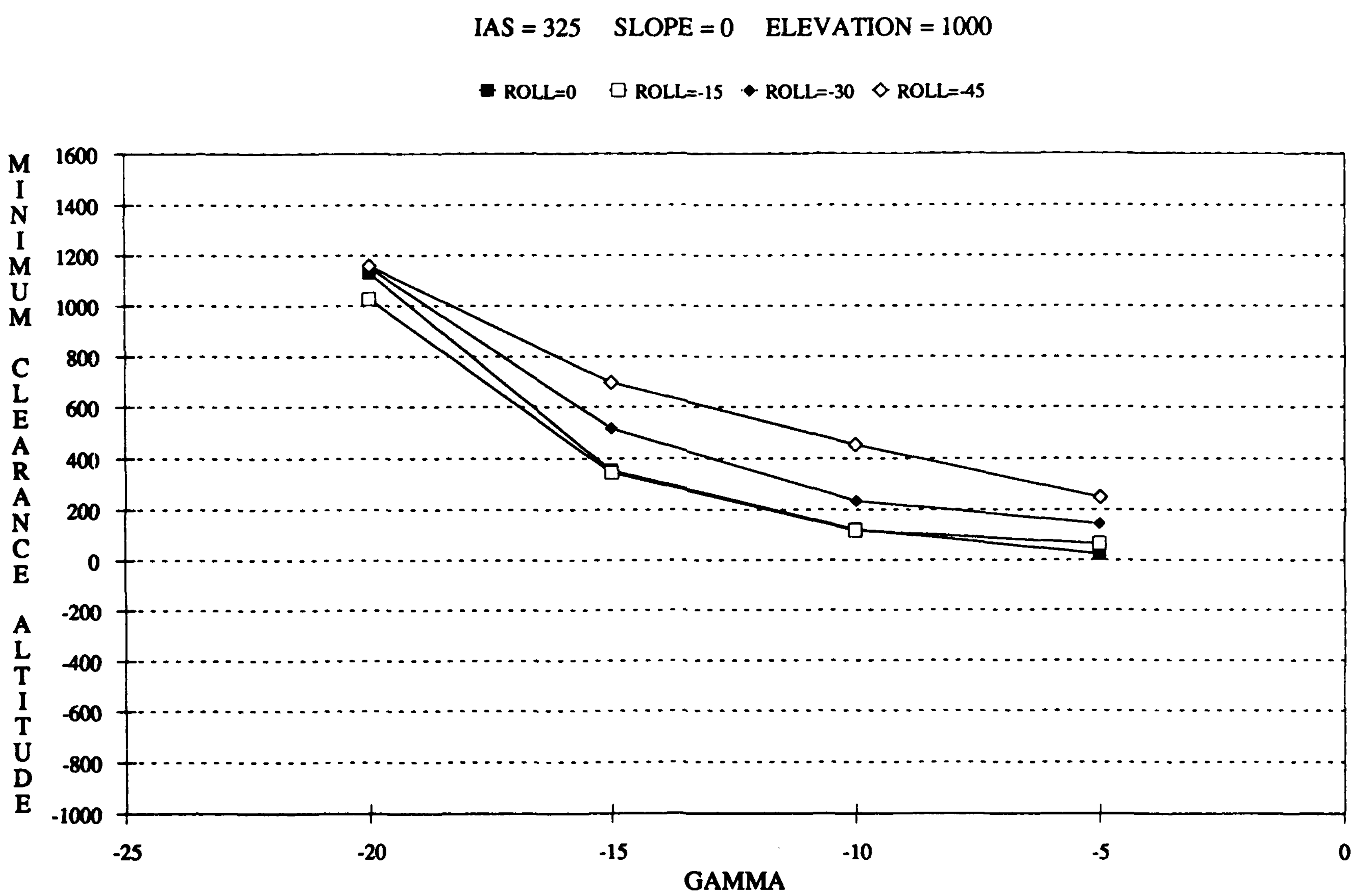


Figure 32. Minimum clearance as a function of gamma for pilot model: IAS=325, Slope=0, & Elevation=1000.

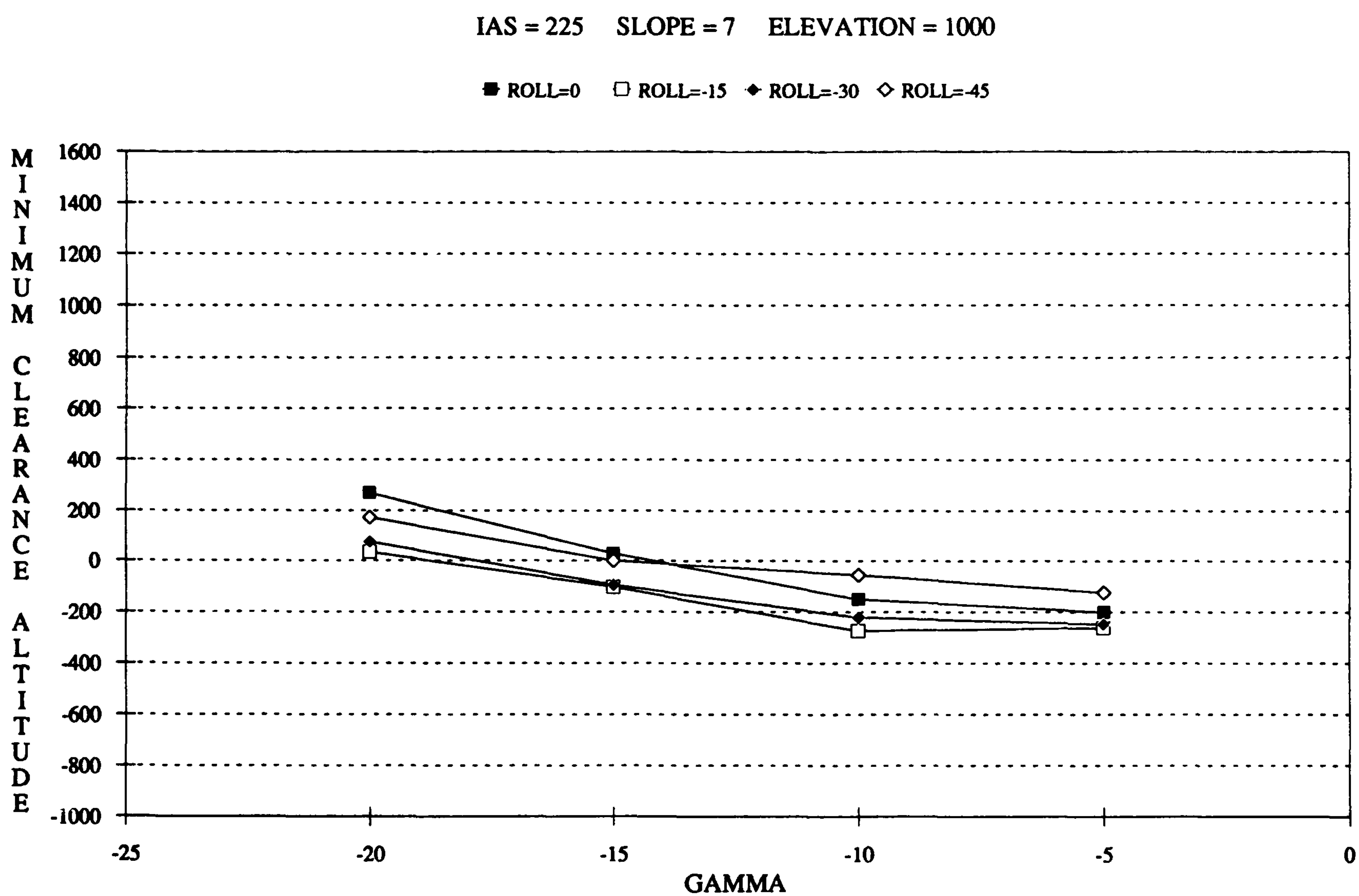


Figure 33. Minimum clearance as a function of gamma for pilot model: IAS=225, Slope=7, & Elevation=1000.

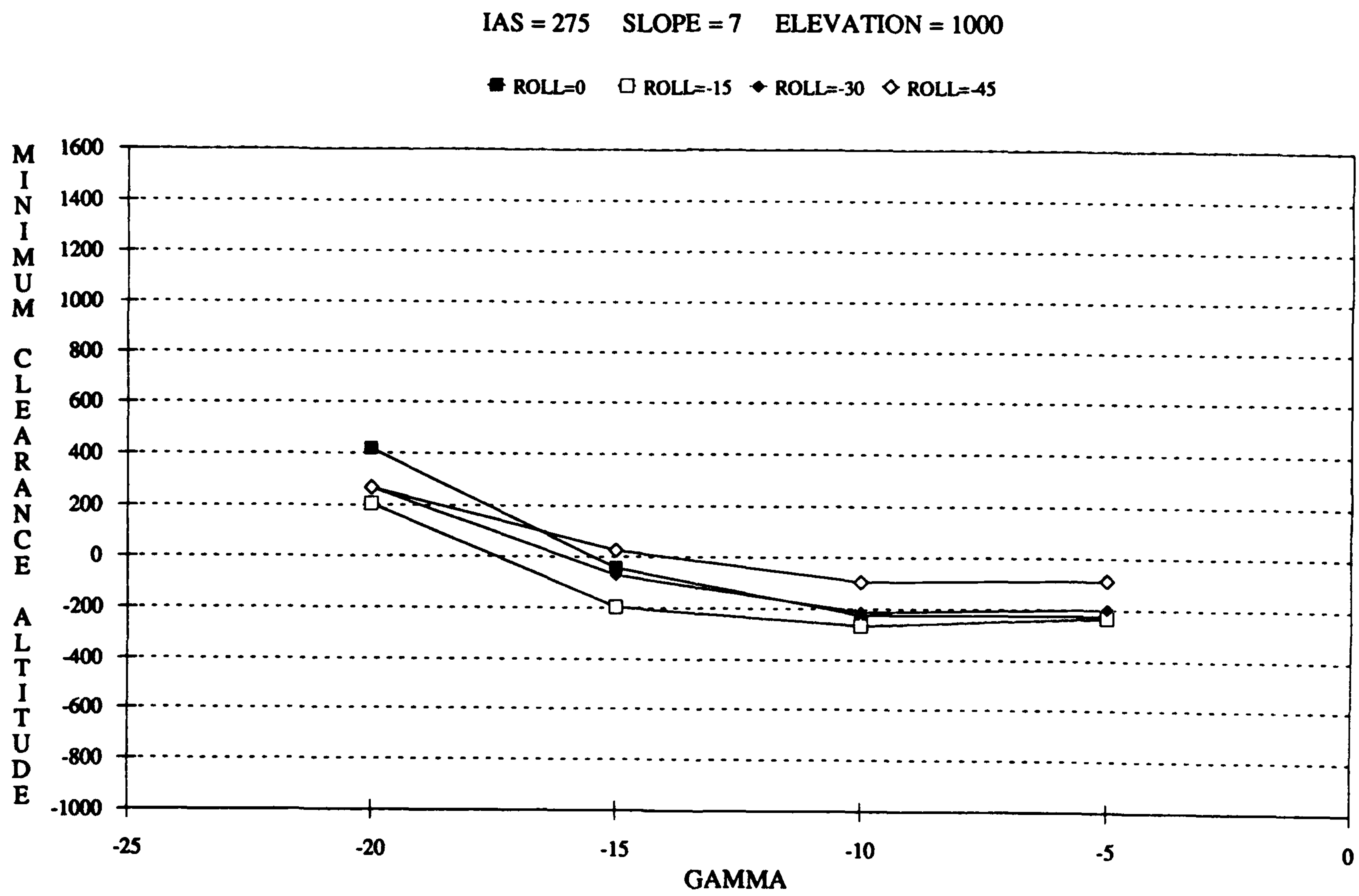


Figure 34. Minimum clearance as a function of gamma for pilot model: IAS=275, Slope=7, & Elevation=1000.

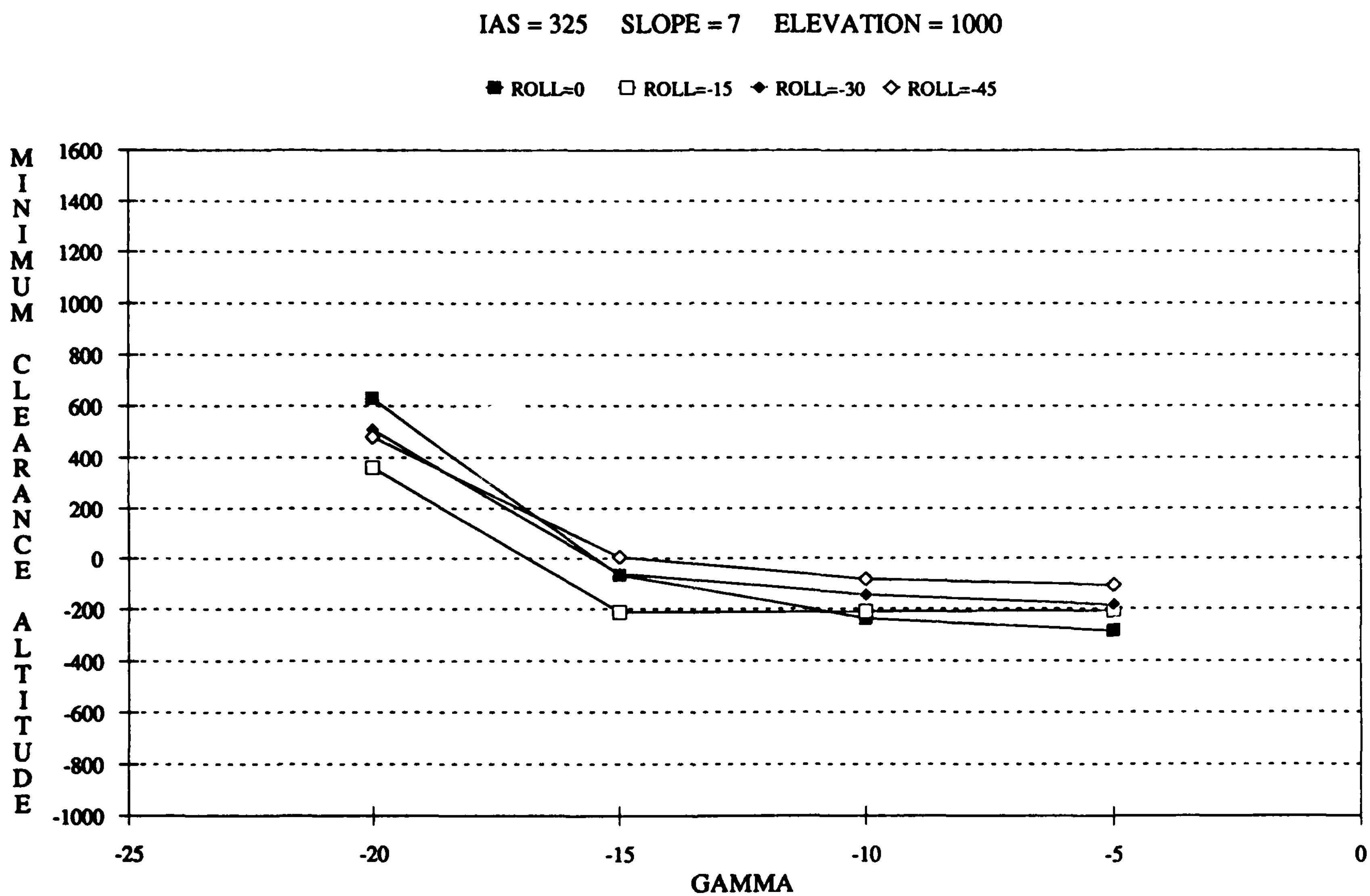


Figure 35. Minimum clearance as a function of gamma for pilot model: IAS=325, Slope=7, & Elevation=1000.

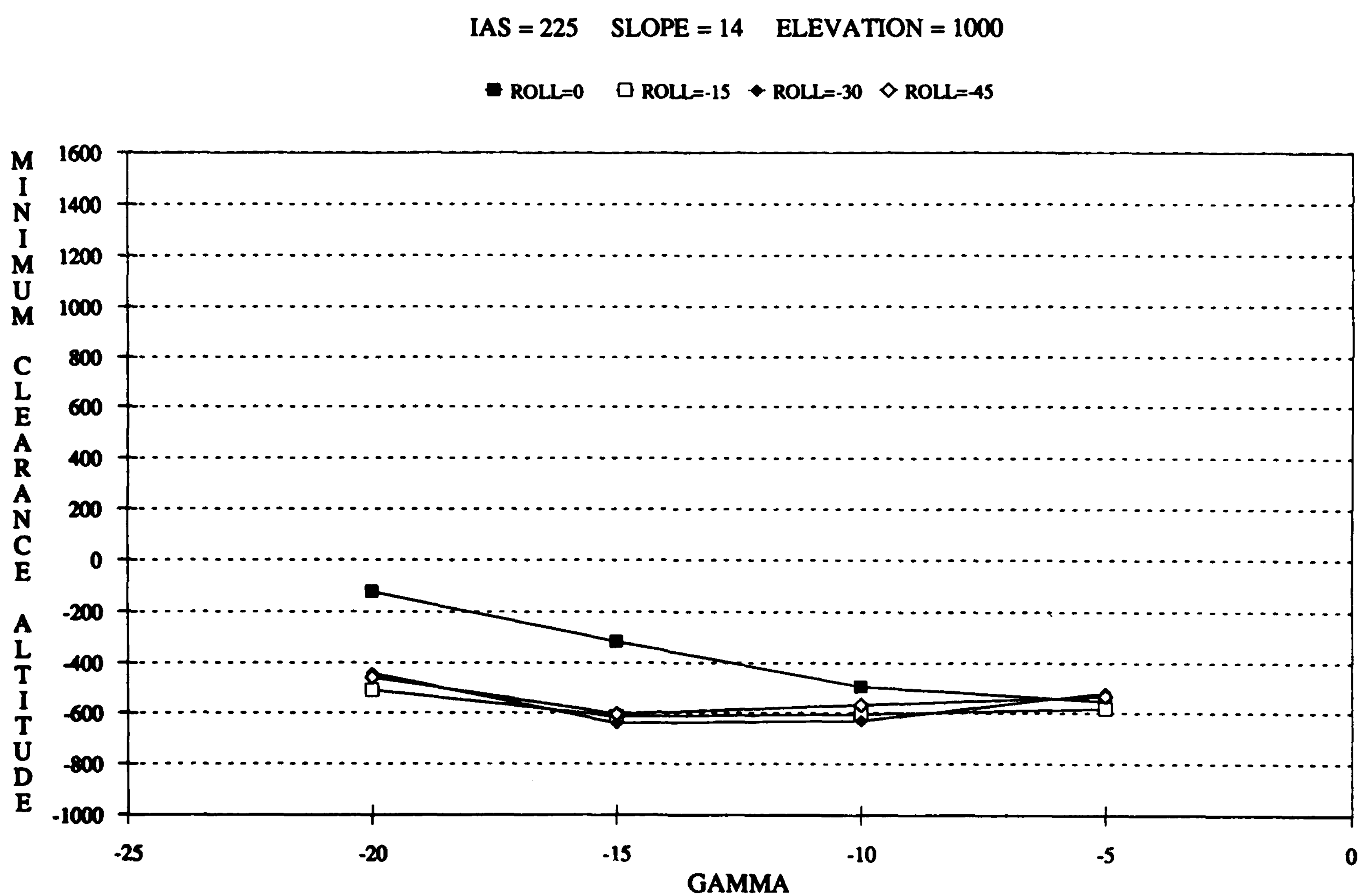


Figure 36. Minimum clearance as a function of gamma for pilot model: IAS=225, Slope=14, & Elevation=1000.

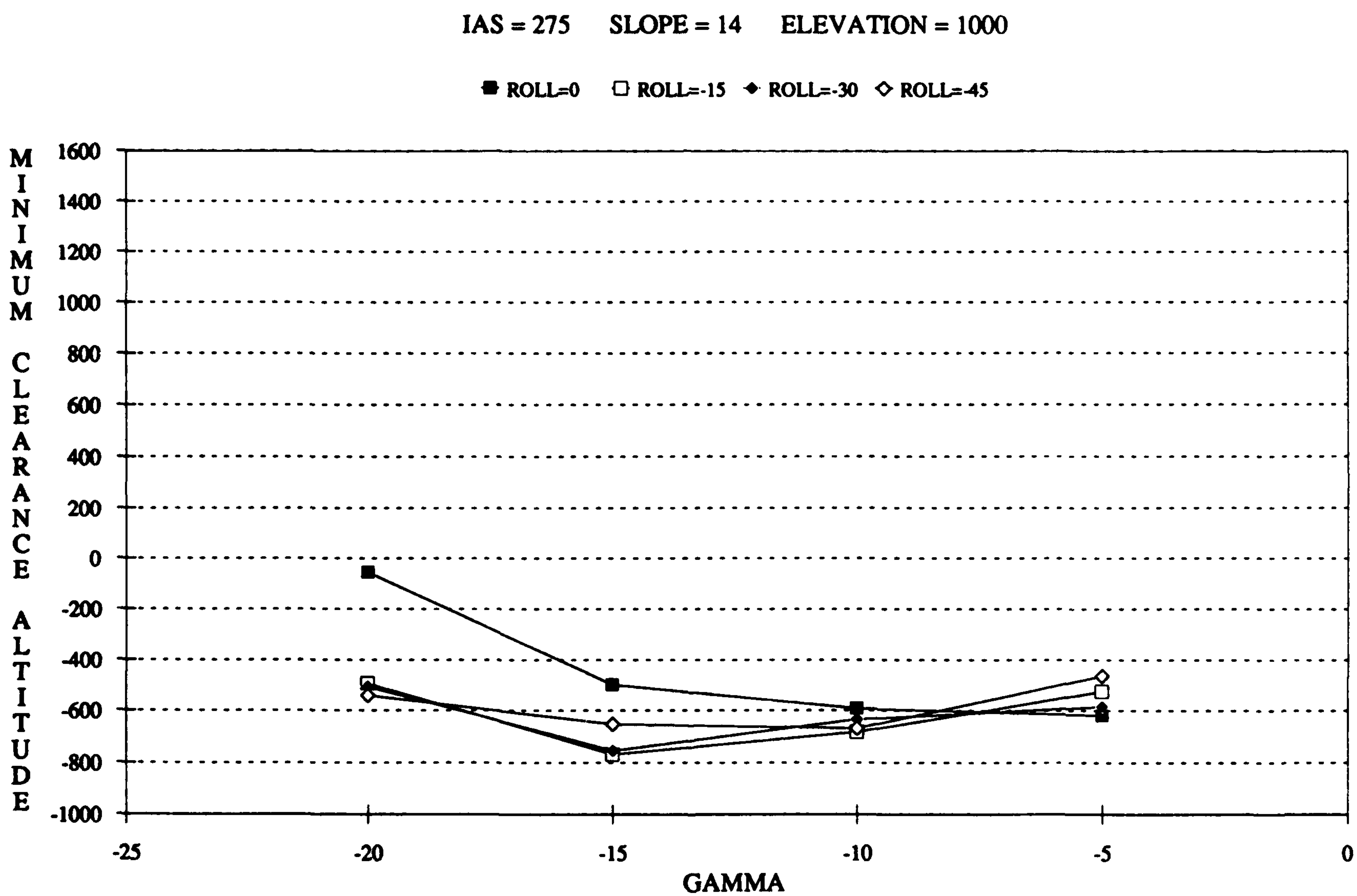


Figure 37. Minimum clearance as a function of gamma for pilot model: IAS=275, Slope=14, & Elevation=1000.

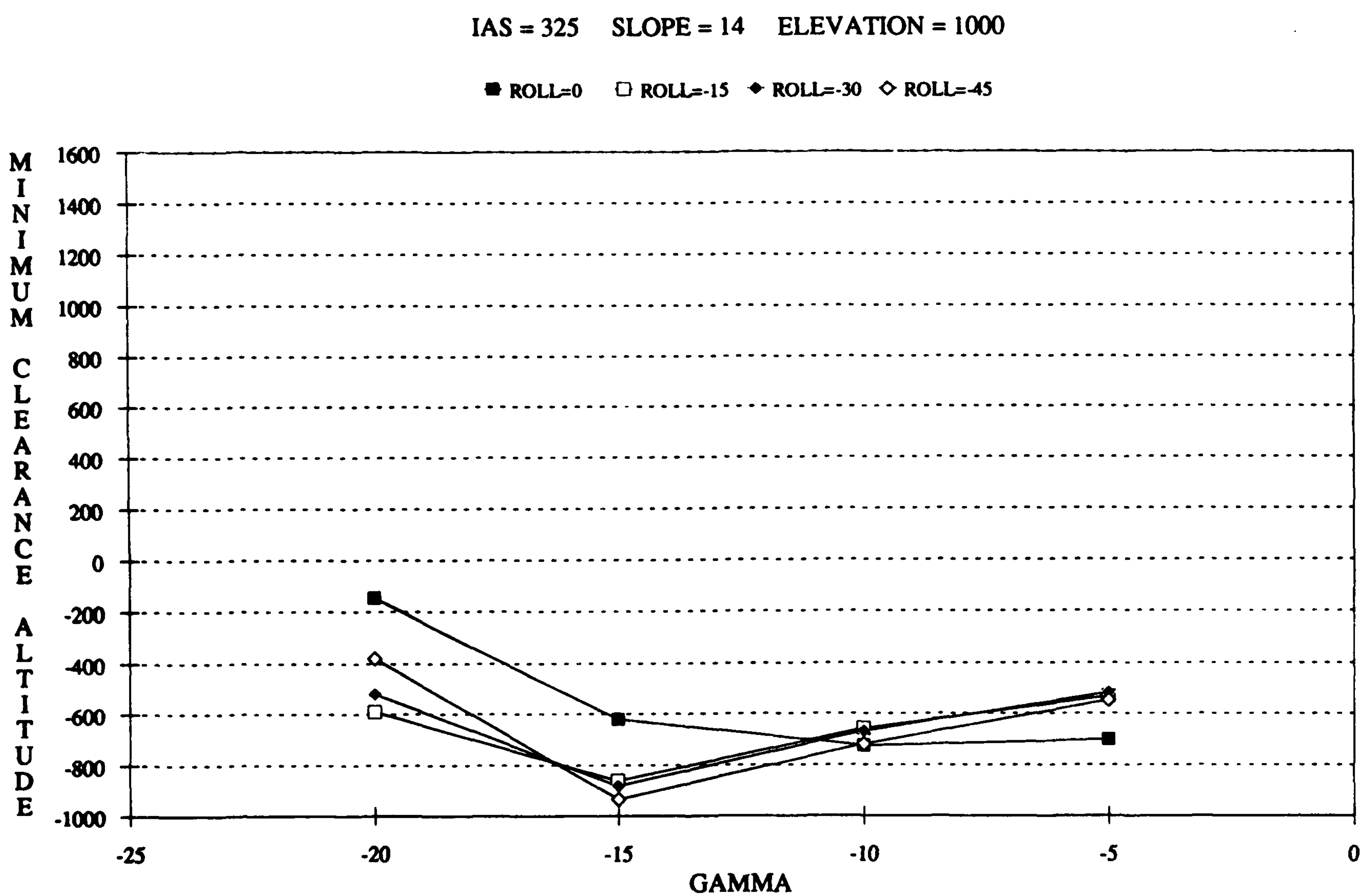


Figure 38. Minimum clearance as a function of gamma for pilot model: IAS=325, Slope=14 & Elevation=1000.

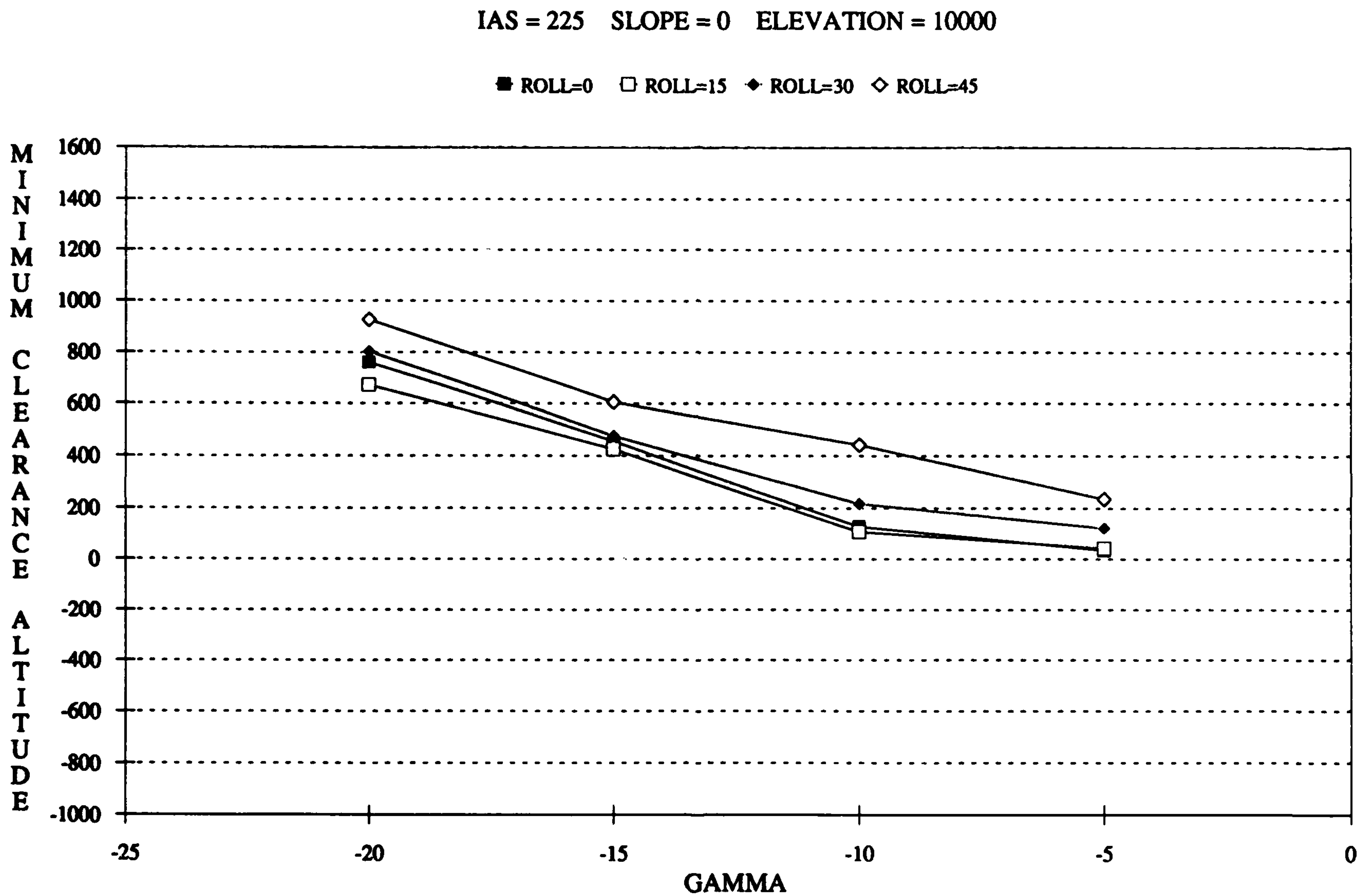


Figure 39. Minimum clearance as a function of gamma for pilot model: IAS=225, Slope=0, & Elevation=10000.

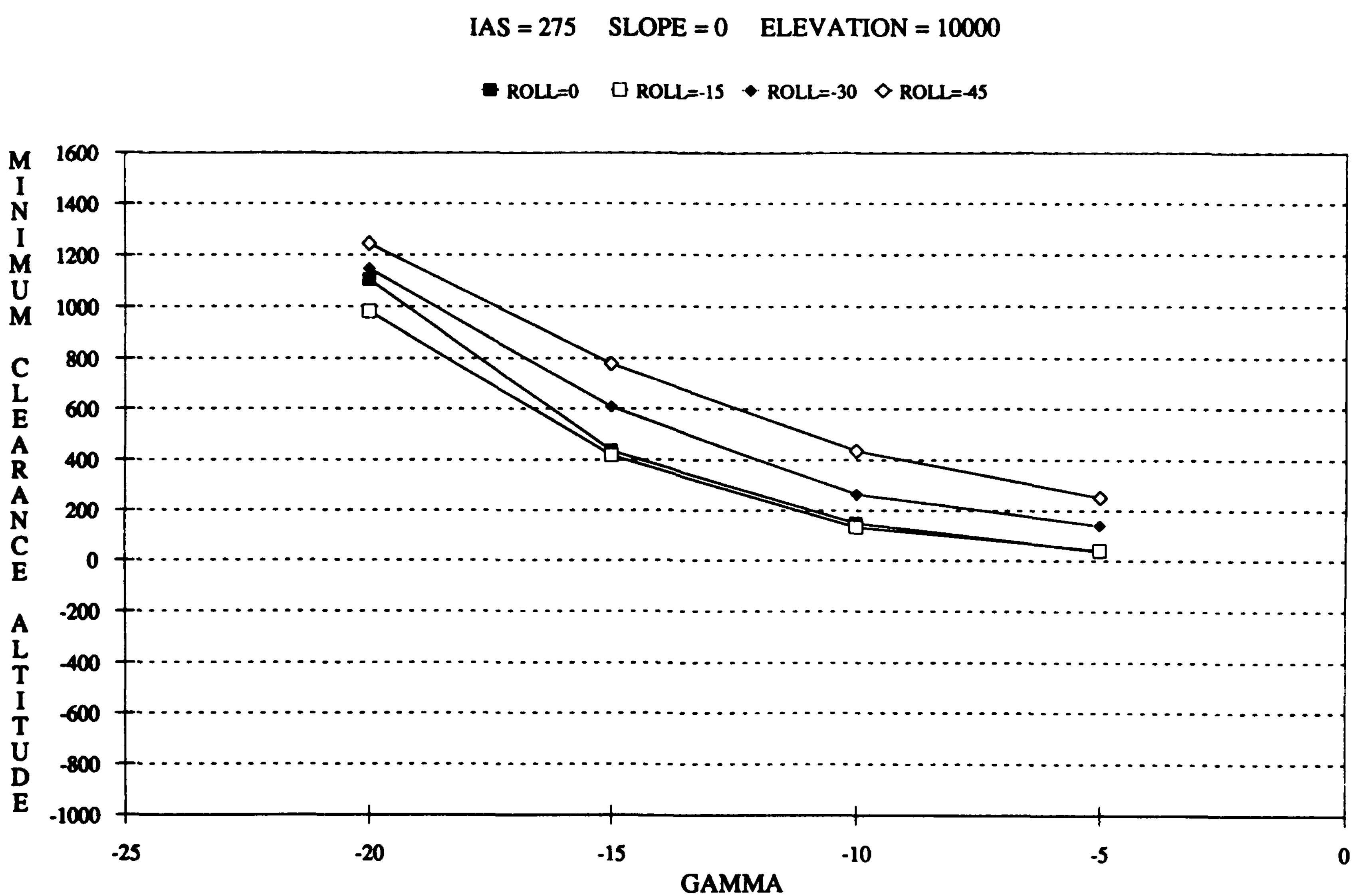


Figure 40. Minimum clearance as a function of gamma for pilot model: IAS=275, Slope=0, & Elevation=10000.

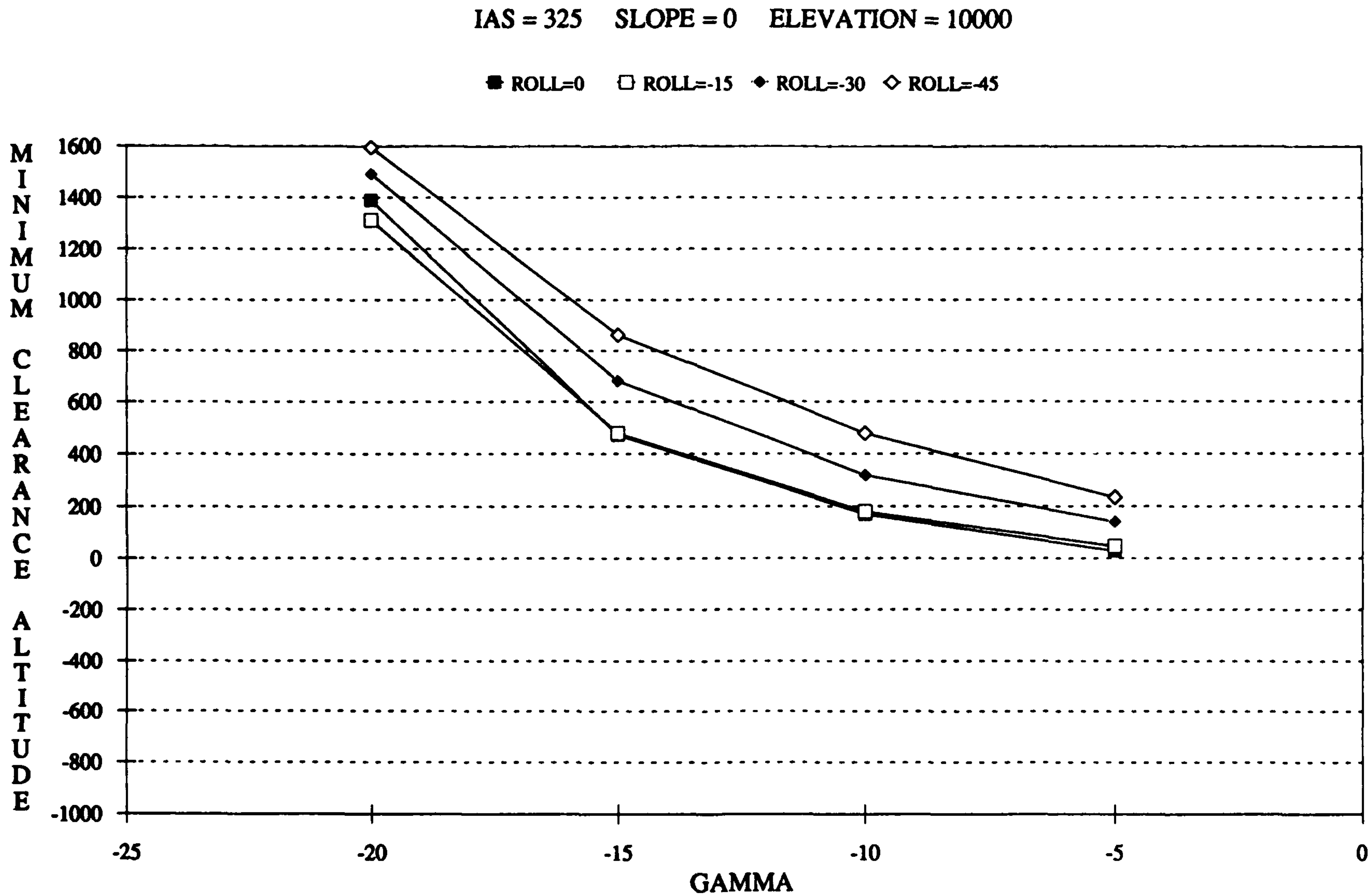


Figure 41. Minimum clearance as a function of gamma for pilot model: IAS=325, Slope=0, & Elevation=10000.

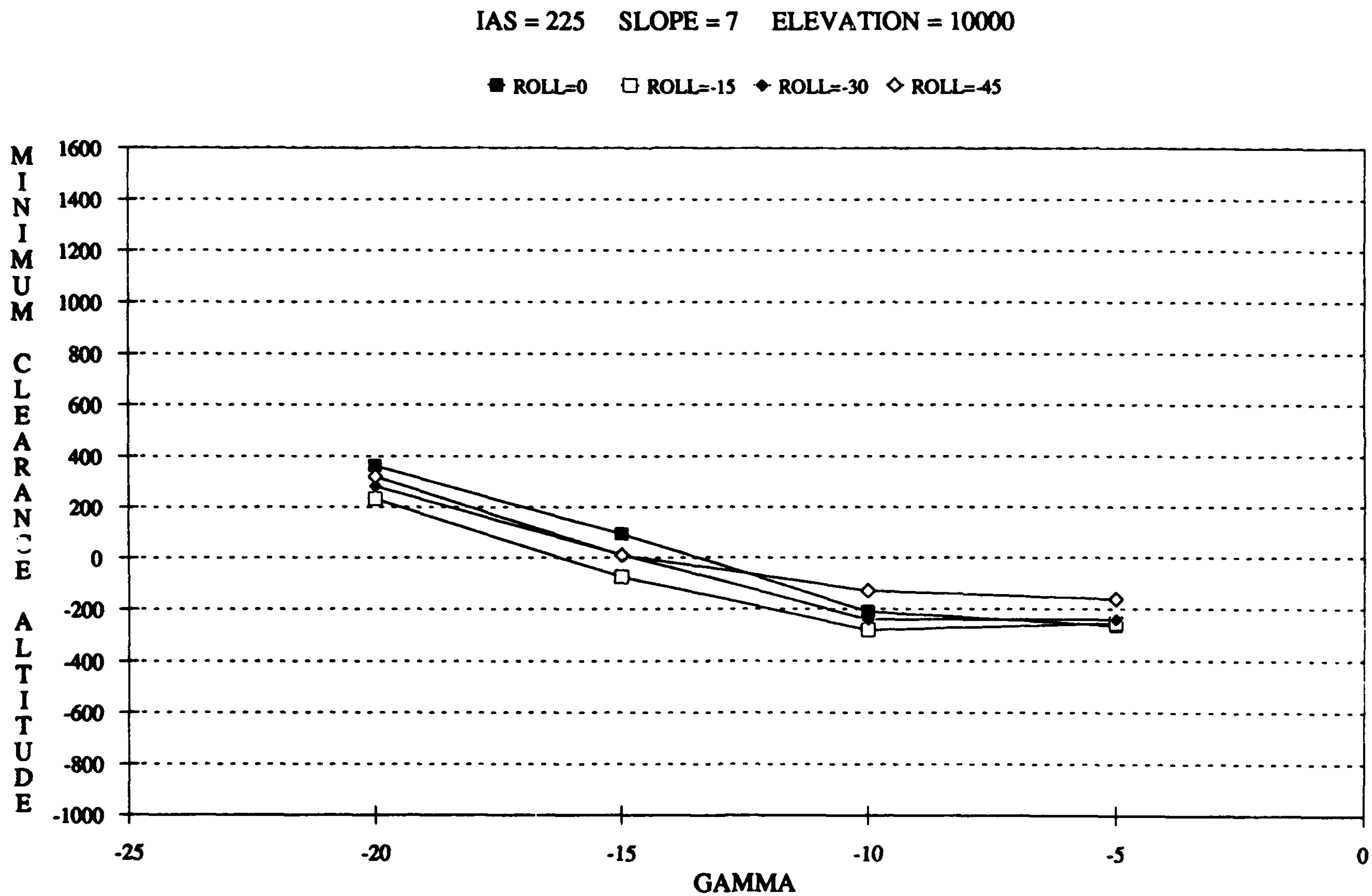


Figure 42. Minimum clearance as a function of gamma for pilot model: IAS=225, Slope=7, & Elevation=10000.

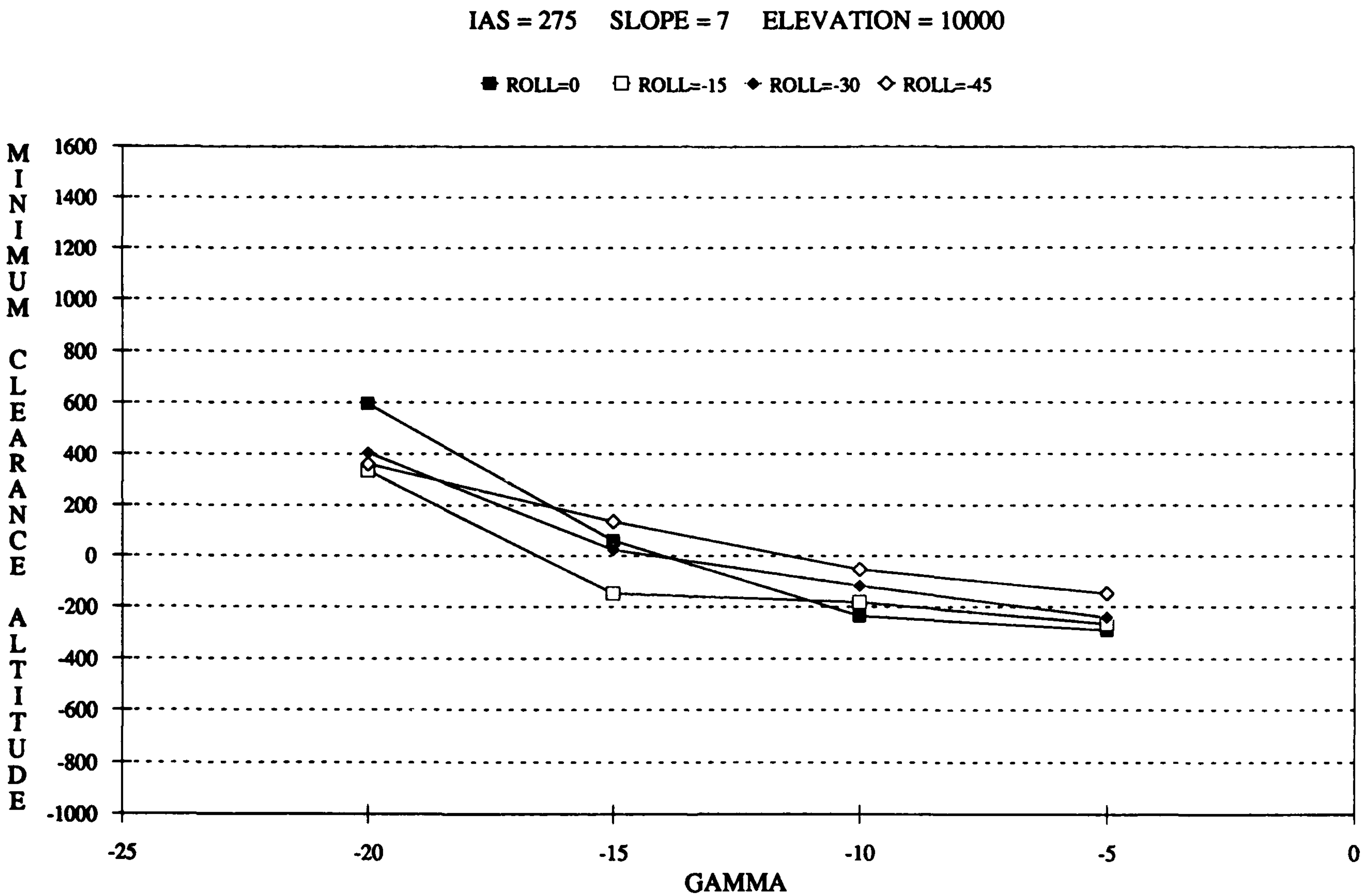


Figure 43. Minimum clearance as a function of gamma for pilot model: IAS=275, Slope=7, & Elevation=10000.

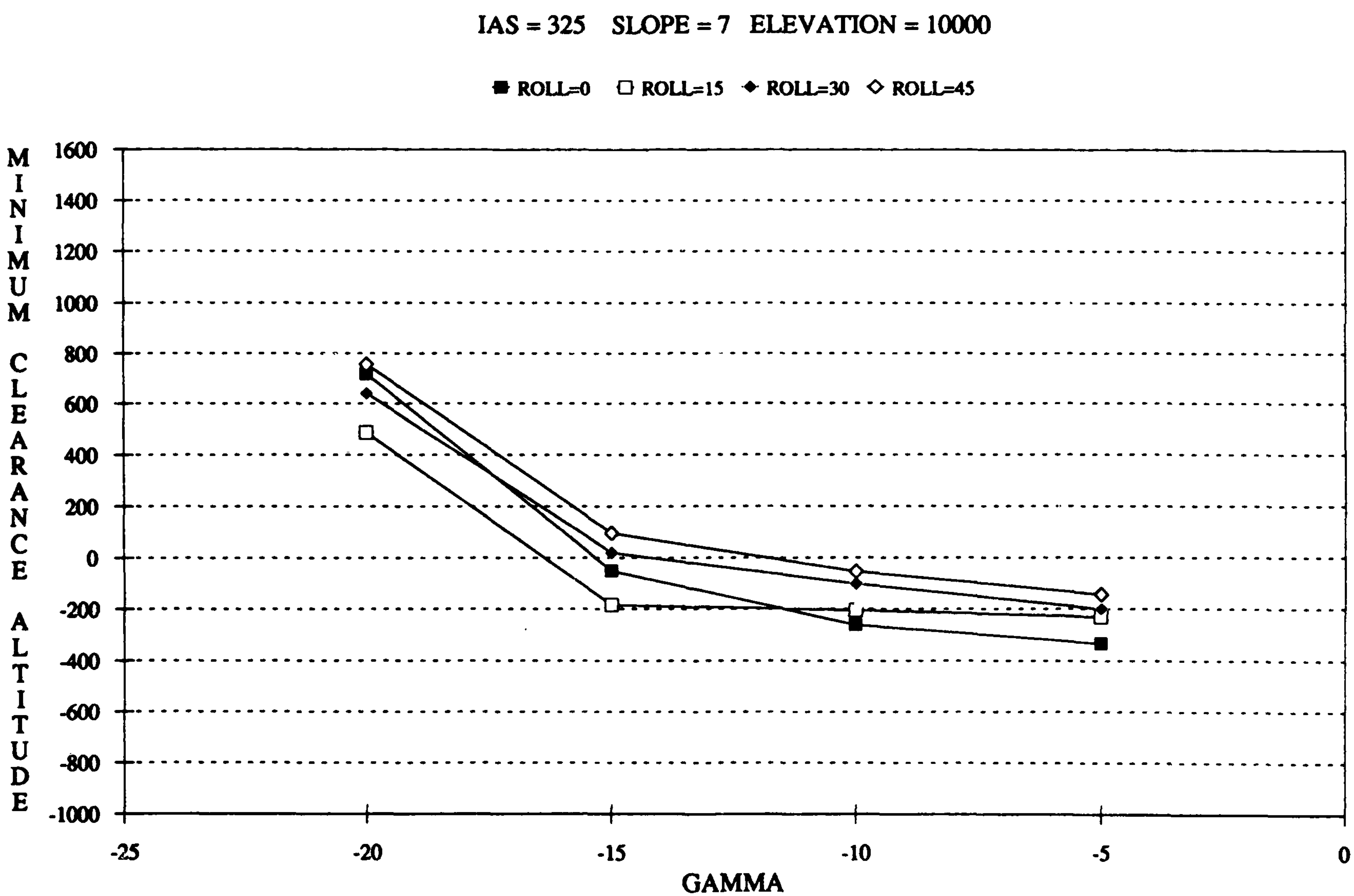


Figure 44. Minimum clearance as a function of gamma for pilot model: IAS=325, Slope=7, & Elevation=10000.

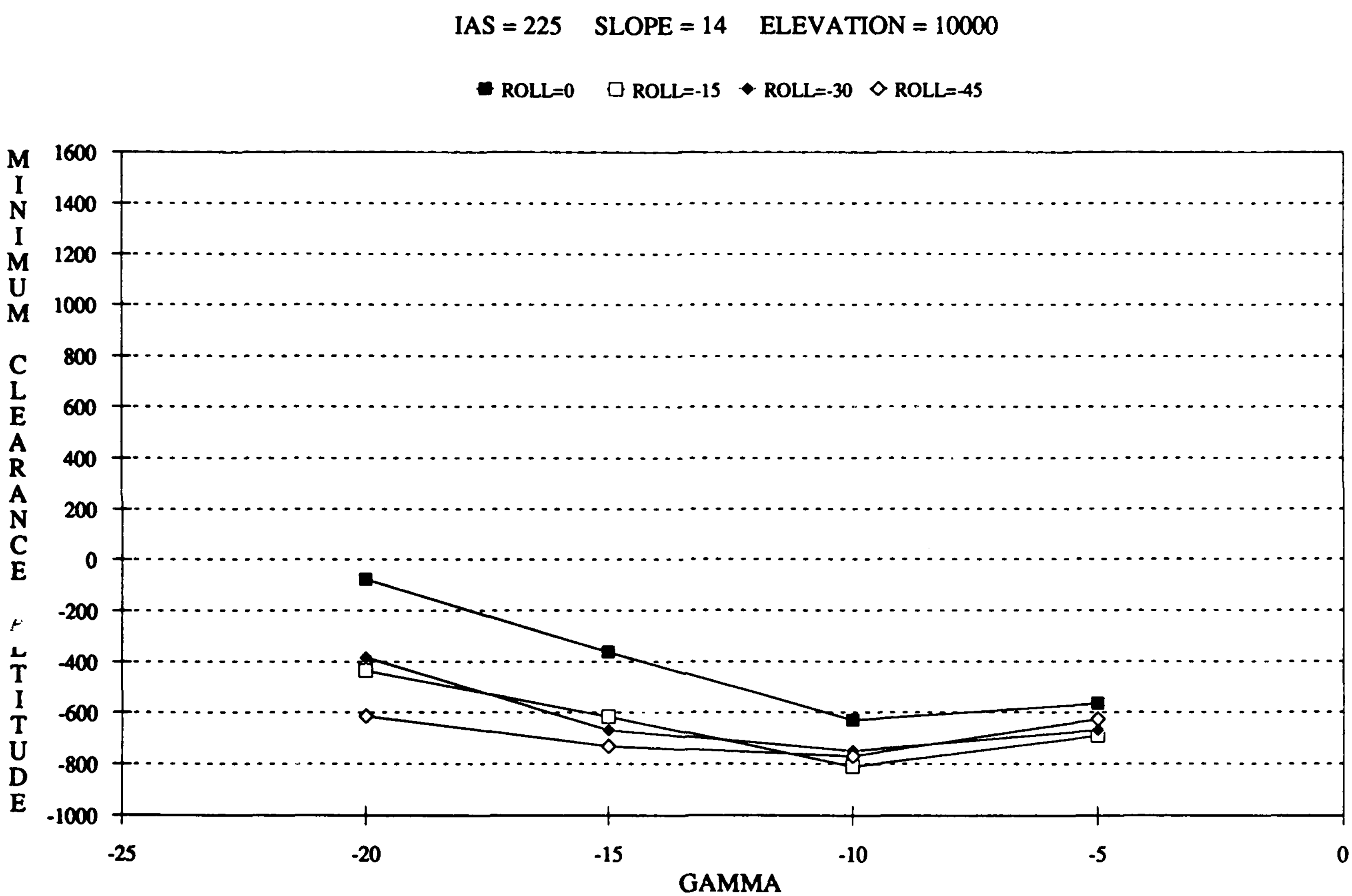


Figure 45. Minimum clearance as a function of gamma for pilot model: IAS=225, Slope=14, & Elevation=10000.

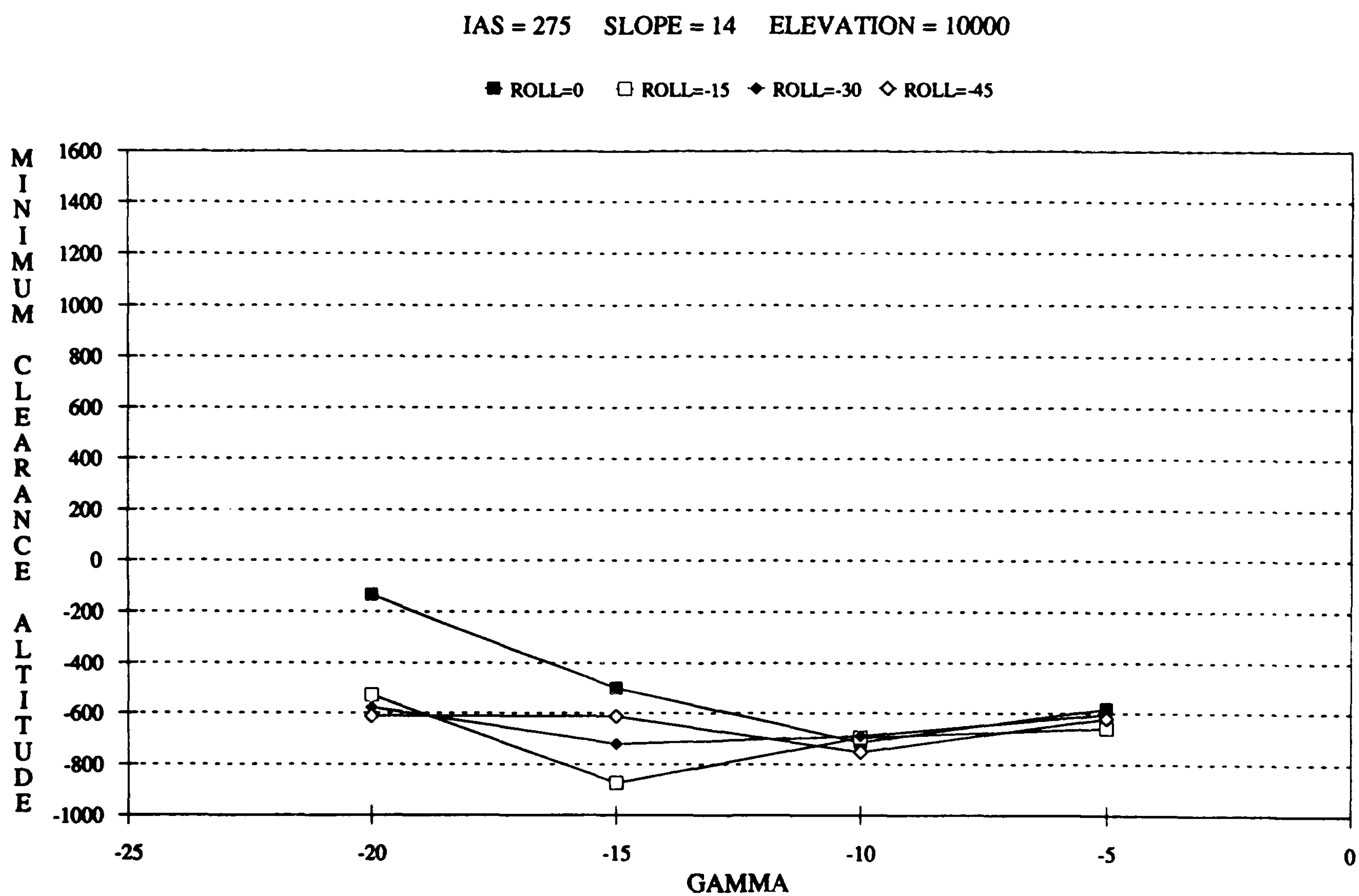


Figure 46. Minimum clearance as a function of gamma for pilot model: IAS=275, Slope=14, & Elevation=10000.

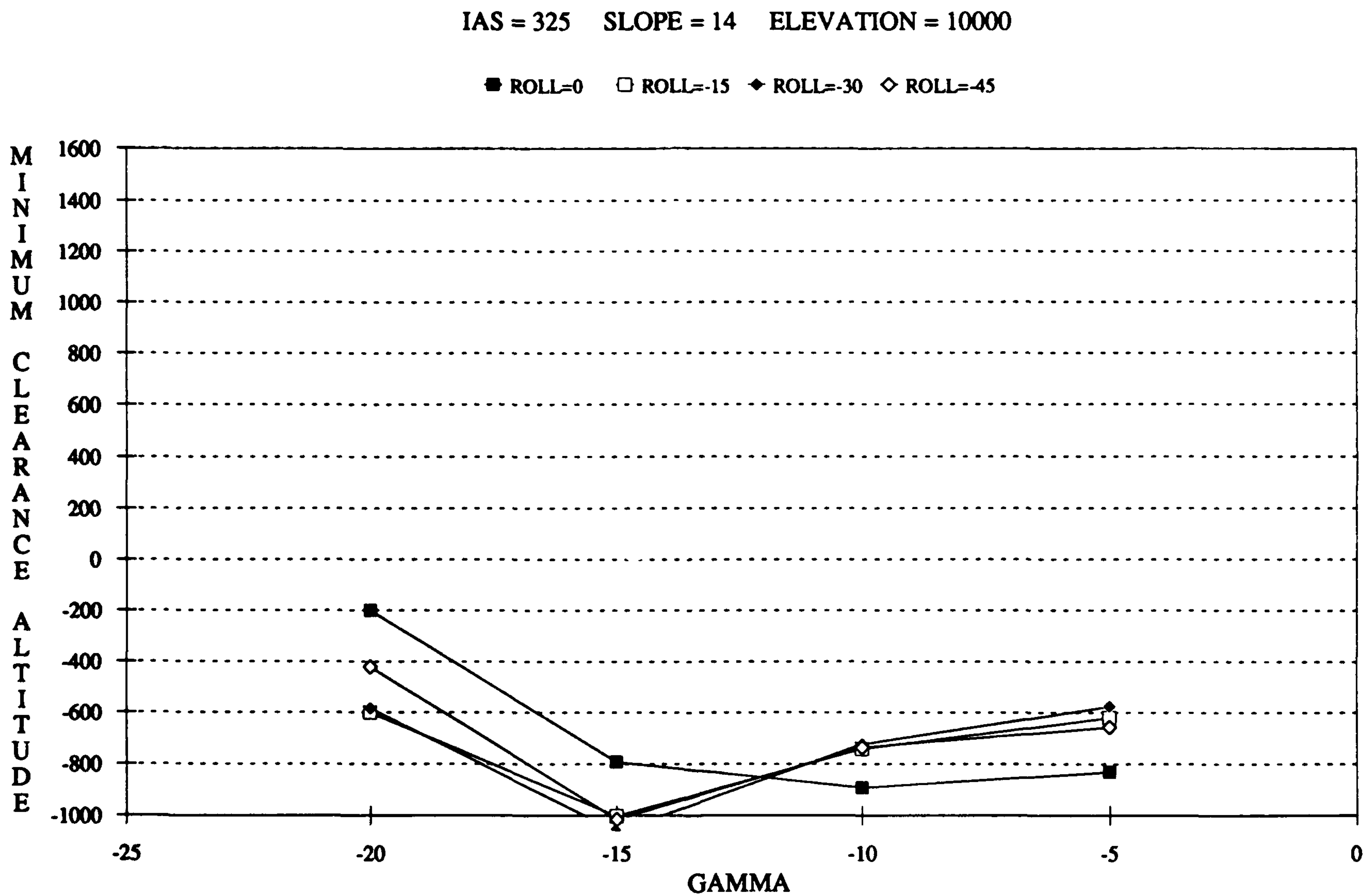


Figure 47. Minimum clearance as a function of gamma for pilot model: IAS=325, Slope=14, Elevation=10000.

Airspeed Effects

Comparisons of Figures 30-32, Figures 33-35, and Figures 36-38 provided the analysis for indicated airspeed effects. In a similar fashion to terrain elevation effects, indicated airspeed increases resulted in increased minimum clearances. The effect was also enhanced for the higher gammas. This was anticipated since increased minimum clearances were desired by pilots for increased flight path angles and increased airspeeds. The algorithm adequately addressed the effects of indicated airspeed.

Roll Angle Effects

To determine the effects of roll angle, each graph was inspected for the different levels of roll. Each line represented a given roll condition. It was anticipated that minimum clearance would increase as the roll angle increased. A review of Figure 30 supported this hypothesis. Although there was some interaction of the roll lines across the figures, increased roll did generally cause increased minimum clearances. The interaction was typically caused by the zero roll condition and may be due to the fact that the algorithm does not compute a predicted altitude loss due to roll, until a roll greater than five degrees exists.

Flight Path Angle Effects

The effects of flight path angle can be determined by proceeding along each of the roll lines on each of the graphs. A review of Figure 30 indicates gamma generally had the hypothesized effect on minimum clearance. Specifically, increased gammas resulted in increased minimum clearance altitudes. This was generally true of the remaining figures.

Terrain Slope Effects

The effects of terrain slope on minimum clearance altitude can be readily seen by comparing Figures 30, 33, and 36; Figures 31, 34, and 37; and Figures 32, 35, and 38. By doing so, one observes terrain slope had a great effect on the minimum clearance altitude. As terrain slope increased, minimum clearance decreased rapidly, so rapidly that terrain slopes of 7 and 14 degrees yielded minimum clearances well below ground level. The algorithm did not adequately accounted for the effects of terrain slope.

Part 1 Discussion

The above analysis revealed a major discrepancy in the algorithm's ability to provide adequate ground clearance under rising terrain. This inability to provide safe minimum clearances was further aggravated as terrain slope and flight path angles became larger. Figures 38 and 47 clearly show high terrain was improperly accounted for by the GCAS algorithm. A review of Table 4 furthers supports this finding. Table 4 contains the mean minimum clearance altitude of a given independent variable for both Part 1 and Part 2. These findings again reinforce the Phase I conclusion that the effects of slope were not adequately considered by the DCAEXTRP sub-algorithm.

As seen in Table 4, terrain elevation did provide the expected pattern of results in minimum clearances. Consequently, terrain elevation was held constant and was not an independent variable during Phase II-Part 2. Gamma was the only other variable that provided the expected pattern of means, but due to gamma's interaction with terrain slope, discussed previously, the gamma variable was retained as a variable of interest in Part 2. Because they failed to provide the expected pattern of mean minimum clearances (Table 4), both the airspeed and roll angle variables were retained for evaluation during Part 2.

Table 4. Mean minimum clearance for each of the Phase II independent variables for both Part 1 and Part 2.

I.V.	Condition	Part 1 Mean	Part 1 S.D.	Part 2 Mean	Part 2 S.D.
Terrain Elevation	1000	-100	554	575	369
	10000	-46	555	N/A	
Airspeed	225	-95	441	397	226
	275	-52	504	590	304
	325	-71	692	760	460
Roll Angle	0	-53	503	458	357
	15	-131	486	550	378
	30	-59	534	613	386
	45	-50	681	675	332
Flight Path Angle (Dive)	5	-233	302	284	230
	10	-214	388	422	280
	15	-103	535	589	209
	20	746	258	999	294
Terrain Slope	0	440	365	440	350
	7	-23	292	577	369
	14	-635	349	714	348

Cubic attempted to correct the problem by revising the algorithm's calculation of the g-onset . Cubic did this by converting the g-onset calculation from a linear model that addressed a look-up table into a fully linear model using the least squares method with the target load held constant. This affected the time-to-target calculations discussed earlier during Phase I. As will be shown in Part 2, this resulted in a great improvement in the performance of the Cubic GCAS algorithm.

Part 2 Results

Prior to further evaluation, the Cubic algorithm was revised to account for the effects of slope. Part 2 evaluated the revised algorithm's ability to adequately provide ground clearance. Since the algorithm was already adequately accounting for terrain elevation effects, terrain elevation was not evaluated during Part 2. Consequently, 50% fewer trials were run for a total of 144 trials. Two additional variables, Cg and Gross weight, were evaluated during Part 2 for an additional 48 trials. As in Part 1, the data were sorted by indicated airspeed and terrain slope, and graphed for minimum clearance as a function of flight path angle (gamma) for all roll angle conditions.

Airspeed Effects

Airspeed effects were evaluated by comparing Figures 48-50, Figures 51-53, and Figures 54-56. Increased minimum clearance altitudes were associated with increased airspeed. No significant deviations from this trend were noted. These comparisons indicate the effects of airspeed were adequately accounted for by the revised Cubic algorithm.

Roll Angle Effects

In a similar manner to the gamma effects, increased roll angles resulted in corresponding increases in the minimum clearance altitudes for Figures 48-54. Only under the high airspeed-high slope conditions did an interaction of the roll lines occur, as evidenced in Figures 55 and 56. Accordingly, the revised Cubic algorithm adequately accounted for the effects of roll angle.

Flight Path Angle Effects

Gamma effects were as predicted. Increased dive angles resulted in increased minimum clearance altitudes (see Figures 48-54). Only Figures 55 and 56 show any deviations away from this pattern. These again were found under the high terrain slope conditions. Comparison between Figures 30-38 with Figures 48-54 reveal similar results, with increased minimum clearances for the higher gamma conditions being generated by the revised algorithm. Given this adjustment, the revised algorithm appears to better account for the effects of flight path angle.

Terrain Slope Effects

To examine the effects of slope, Figures 48, 51, and 54; Figures 49, 52, and 55; and Figures 50, 53, and 56 had to be compared. Generally speaking, increased terrain slope resulted in increased minimum clearance altitude. A comparison of Figures 30-38 with Figures 48-56 indicate the problem originally associated with terrain slope had been corrected. Specifically, the revised algorithm provided increased minimum clearances and resulted in positive ground clearances for all data runs. The former algorithm had impacted the ground numerous times.

Gross Weight and Center of Gravity Effects

To evaluate the effects of gross weight (GW) and center of gravity (Cg), 48 more data runs were performed. The gross weight runs were performed with a constant Cg of 24. Cg runs were performed at a constant GW of 270 thousand pounds. These runs were then graphed as previously described, but with the added variable of GW or Cg. A comparative analysis of Figures 57 & 58 revealed 100 foot differences in minimum clearance altitudes as a result of a gross weight change. This effect was considered minimal after an inspection of Figures 59-61 revealed that changes in the center of gravity consistently resulted in minimum clearance altitude changes of more than two hundred feet. Given the effects Cg plays on minimum clearance altitudes, the algorithm should address the Cg variable. The algorithm as currently written fails to consider Cg and assumes the effects of Cg are negligible.

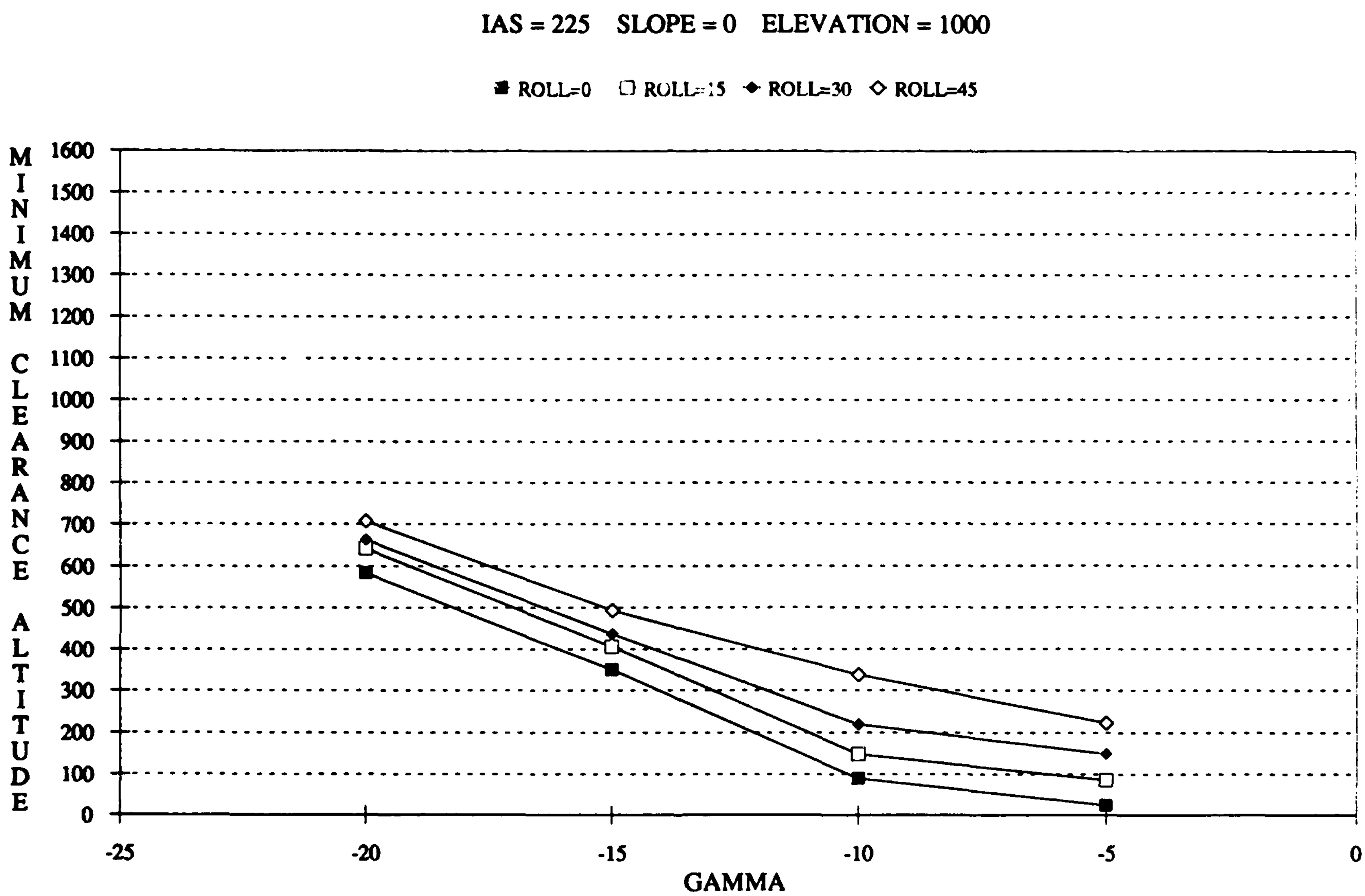


Figure 48. Minimum clearance as a function of gamma for pilot model: IAS=225, Slope=0, & Elevation=1000.

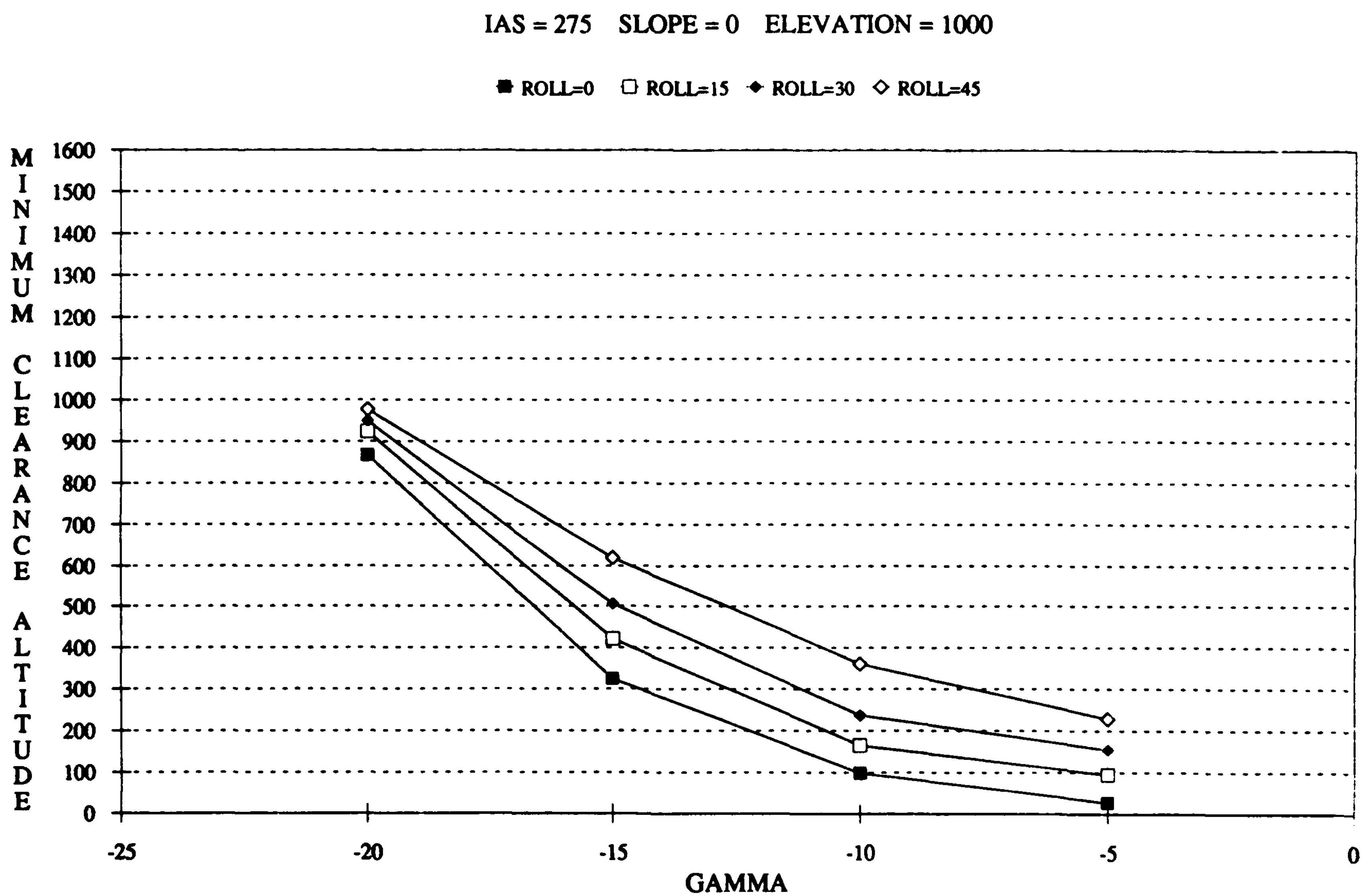


Figure 49. Minimum clearance as a function of gamma for pilot model: IAS=275, Slope=0, & Elevation=1000.

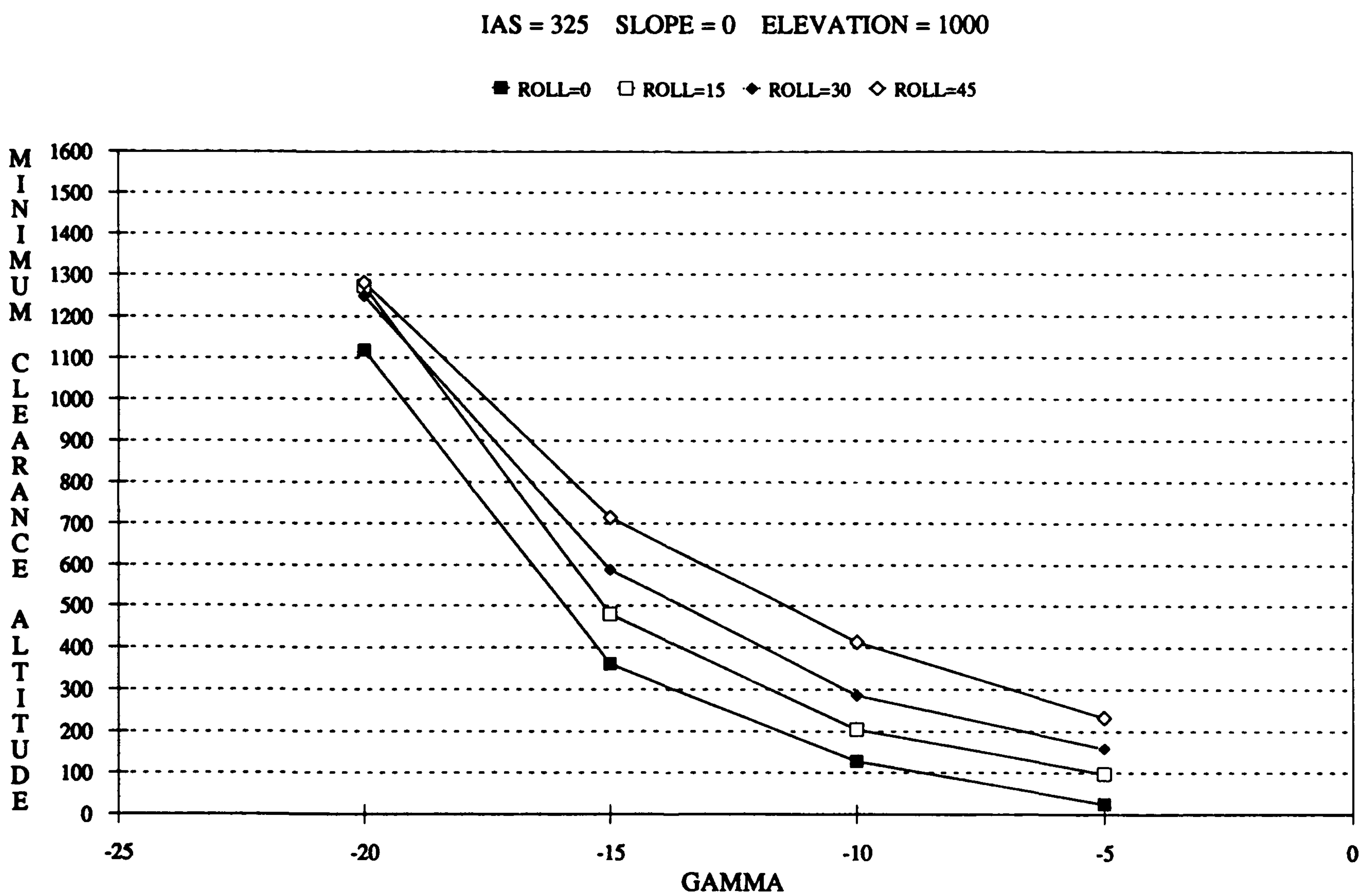


Figure 50. Minimum clearance as a function of gamma for pilot model: IAS=325, Slope=0, & Elevation=1000.

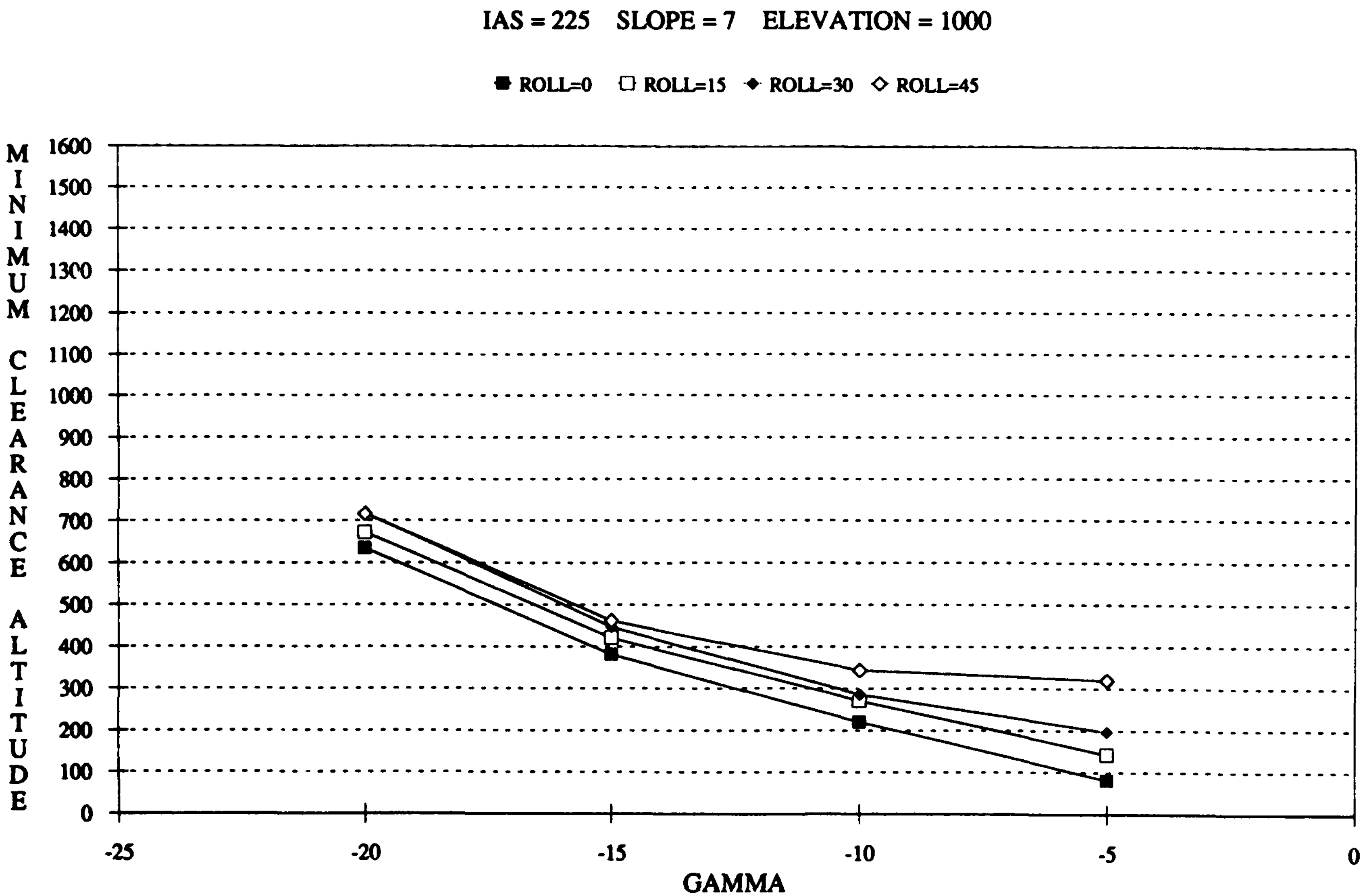


Figure 51. Minimum clearance as a function of gamma for pilot model: IAS=225, Slope=7, & Elevation=1000.

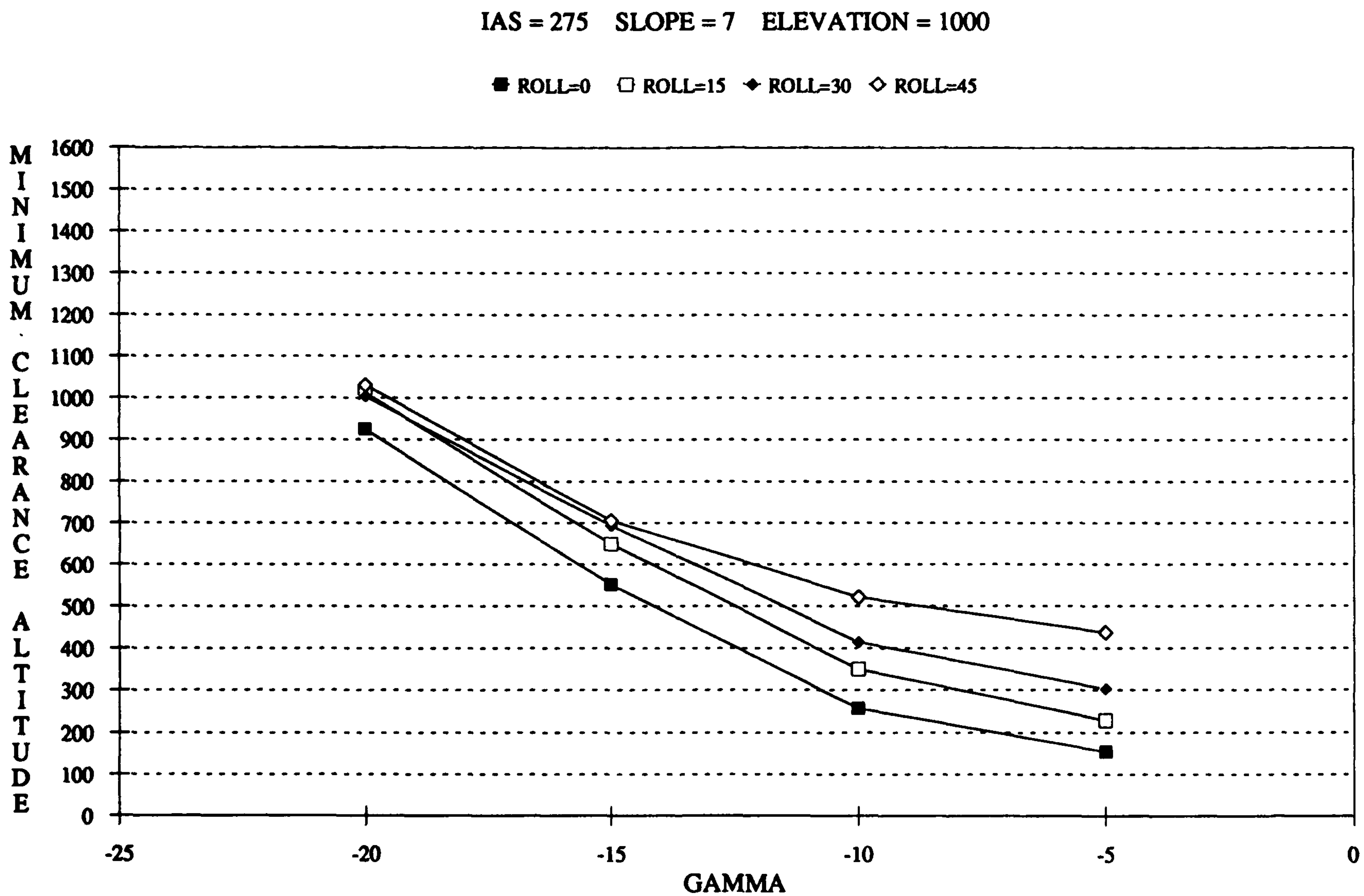


Figure 52. Minimum clearance as a function of gamma for pilot model: IAS=275, Slope=7, & Elevation=1000.

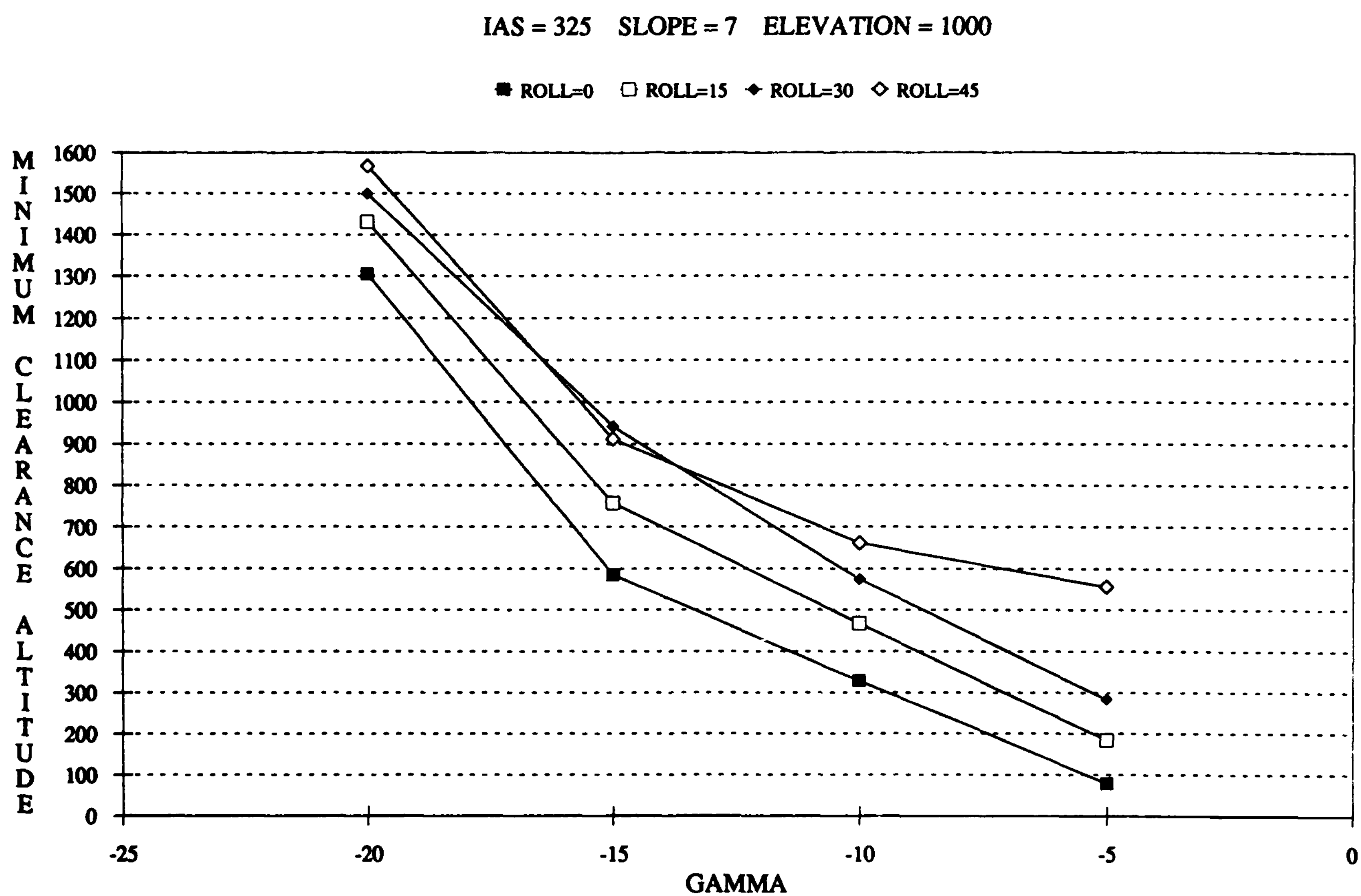


Figure 53. Minimum clearance as a function of gamma for pilot model: IAS=325, Slope=7, & Elevation=1000.

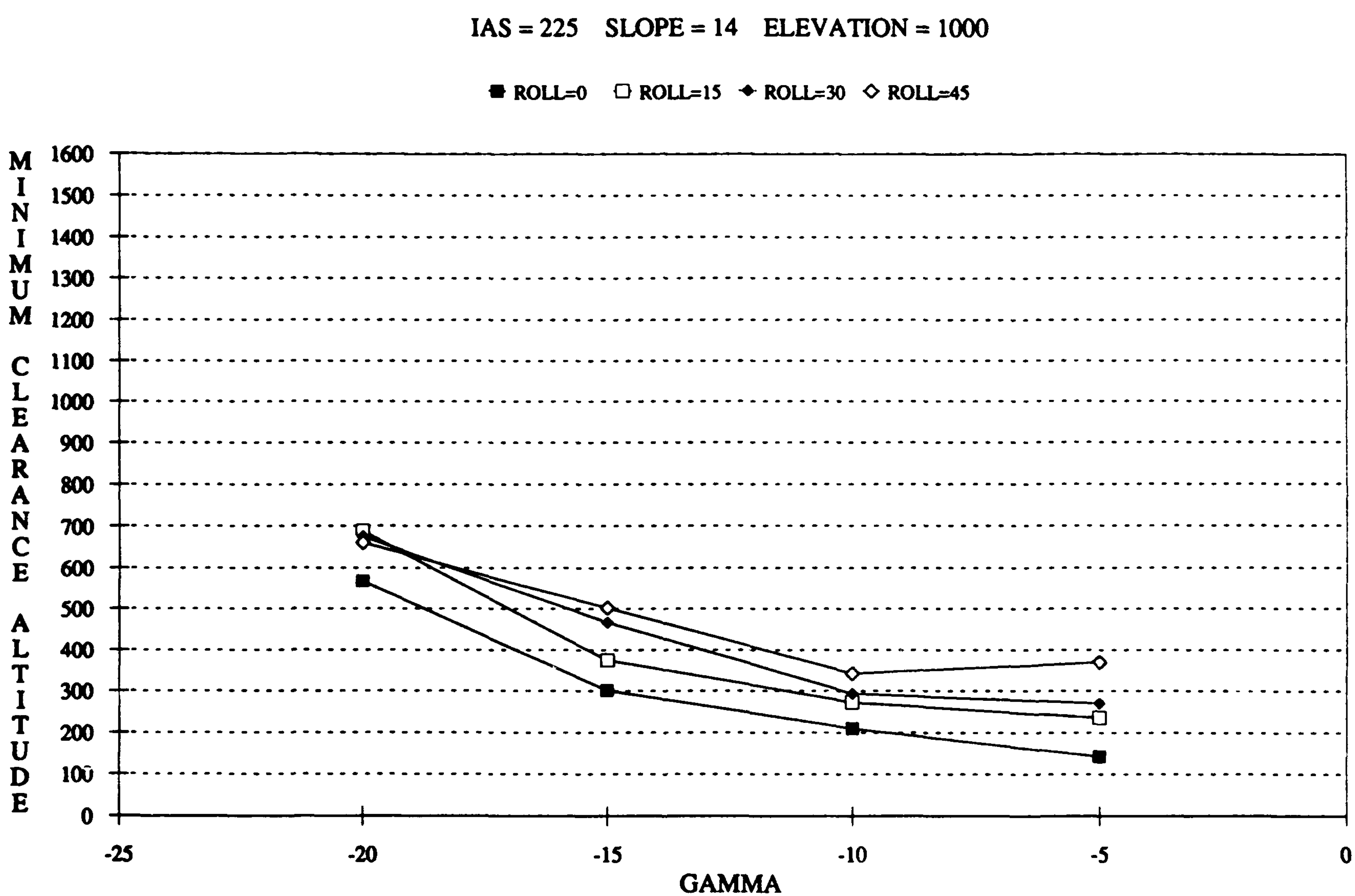


Figure 54. Minimum clearance as a function of gamma for pilot model: IAS=225, Slope=14, & Elevation=1000.

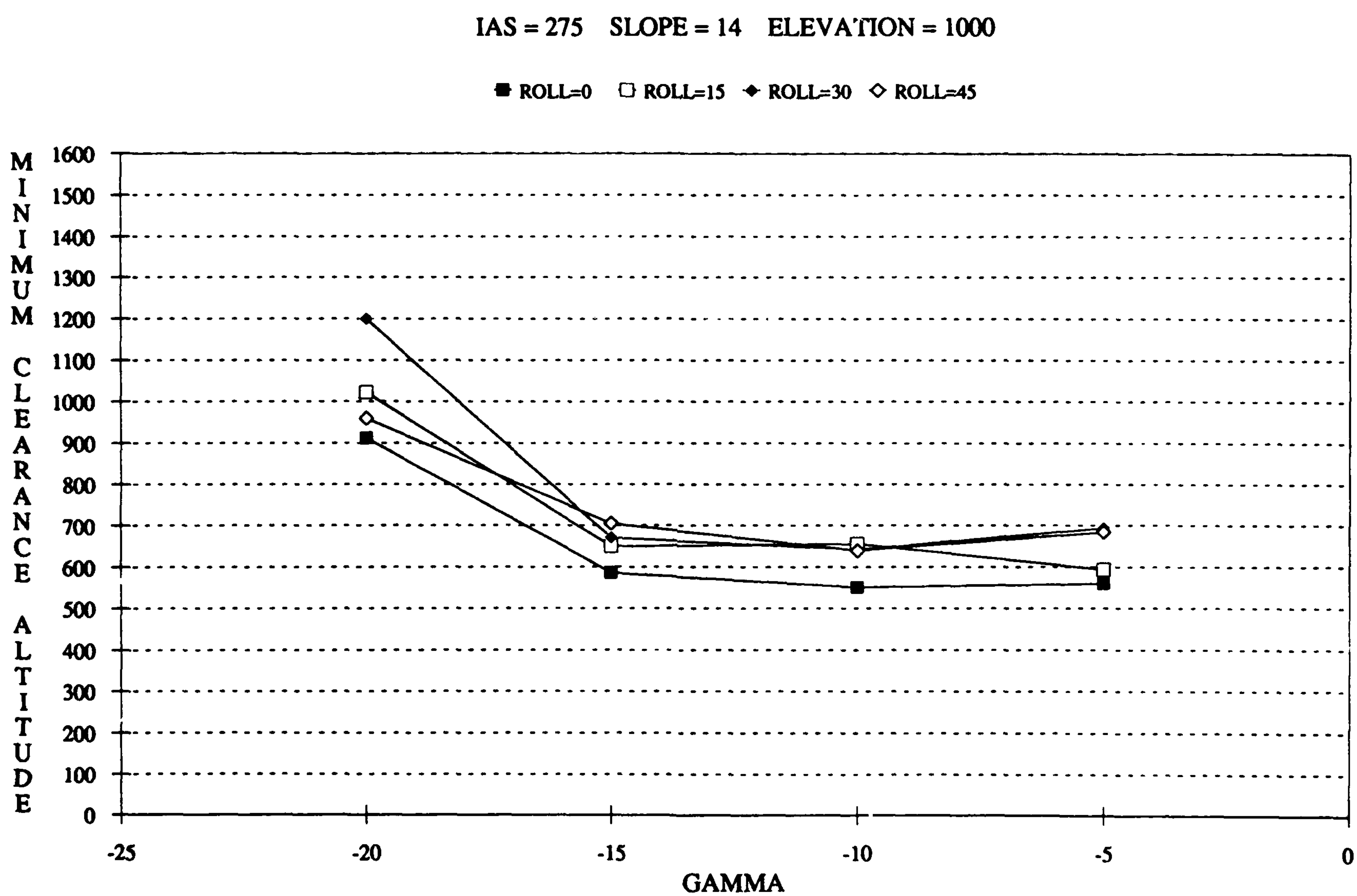


Figure 55. Minimum clearance as a function of gamma for pilot model: IAS=275, Slope=14, & Elevation=1000.

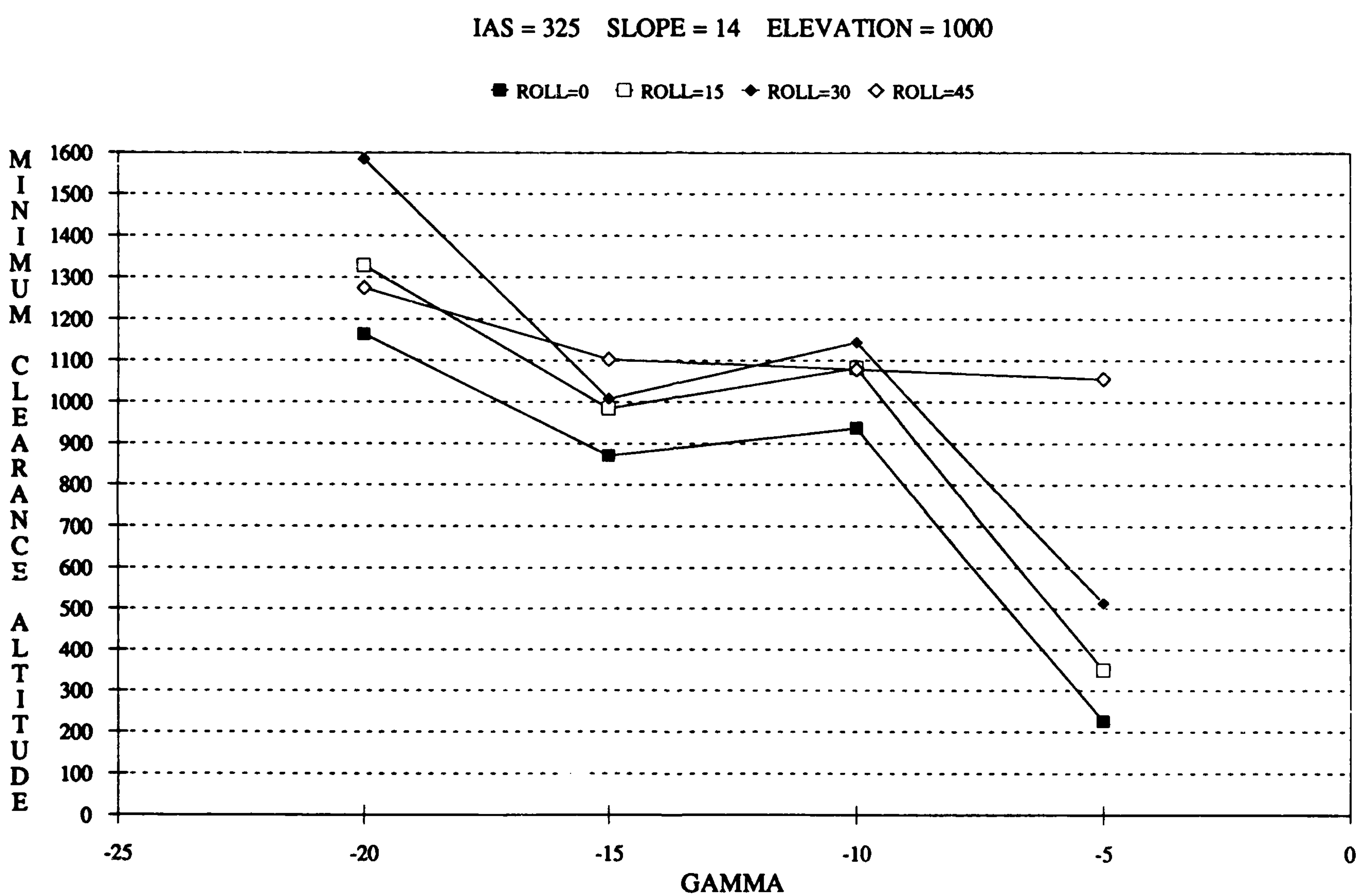


Figure 56. Minimum clearance as a function of gamma for pilot model: IAS=325, Slope=14, & Elevation=1000.

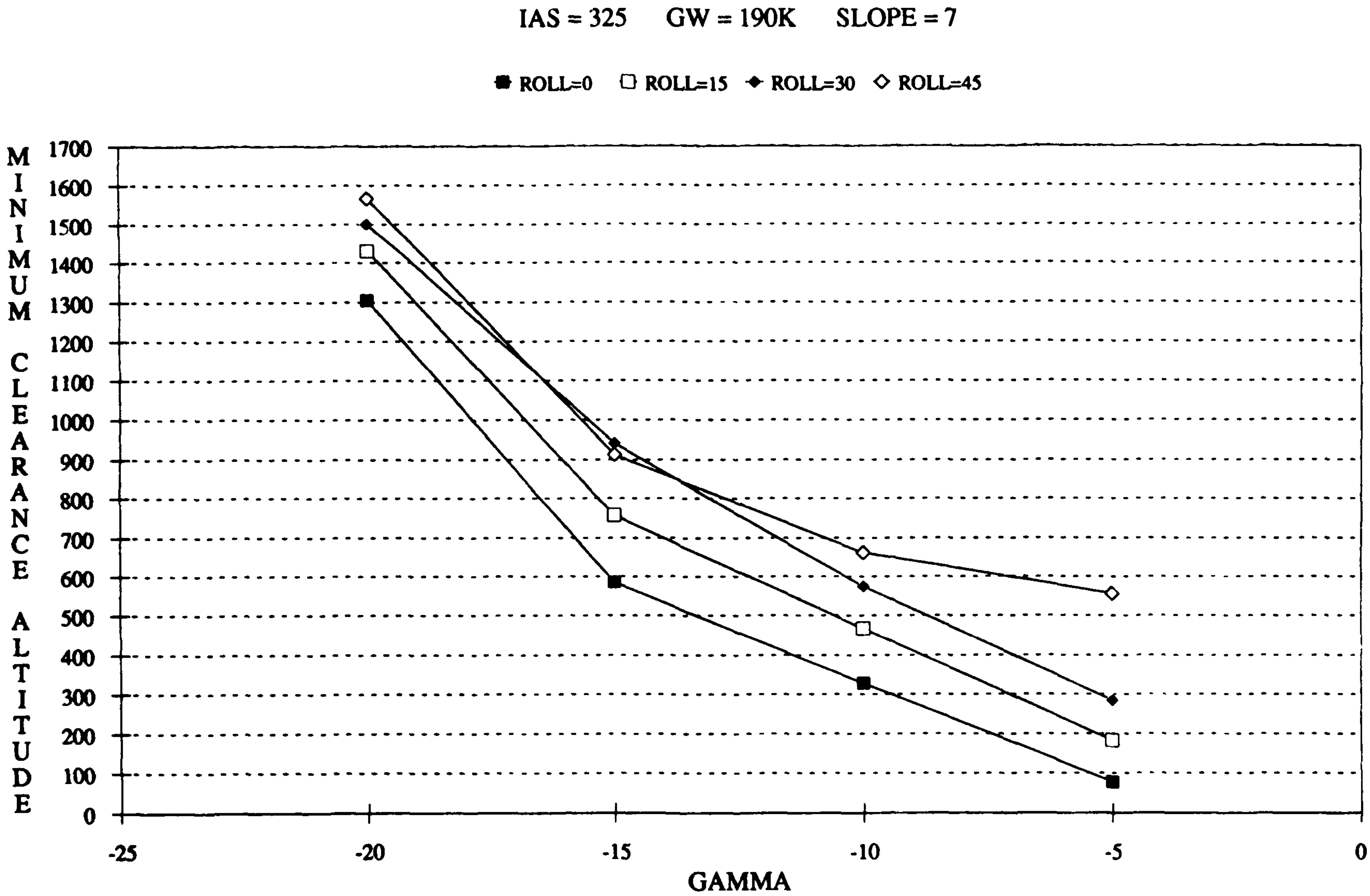


Figure 57. Minimum clearance as a function of gamma for pilot model: IAS=325, Gross Weight=190K, & Slope=7.

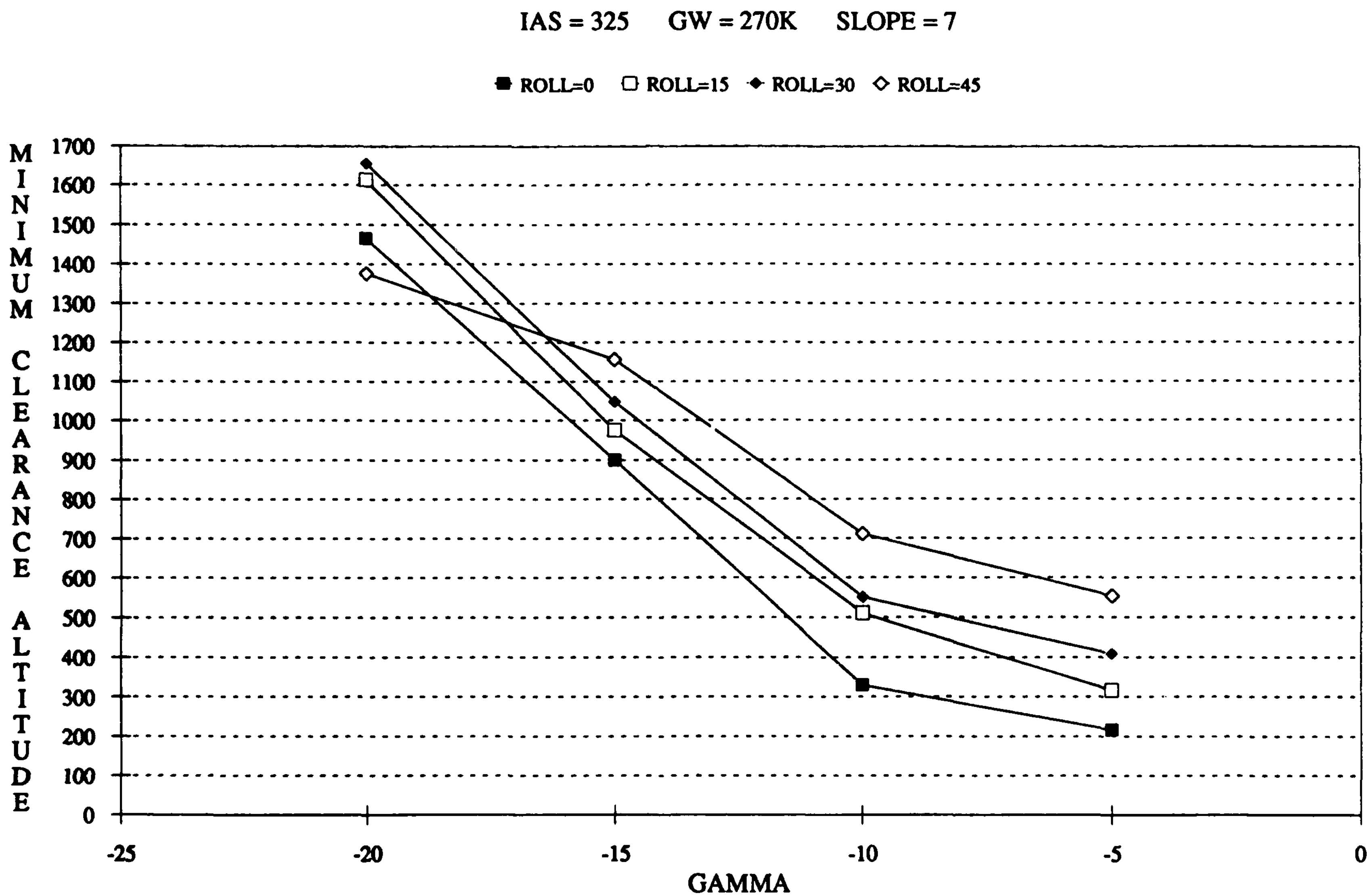


Figure 58. Minimum clearance as a function of gamma for pilot model: IAS=325, Gross Weight= 270K, & Slope=7.

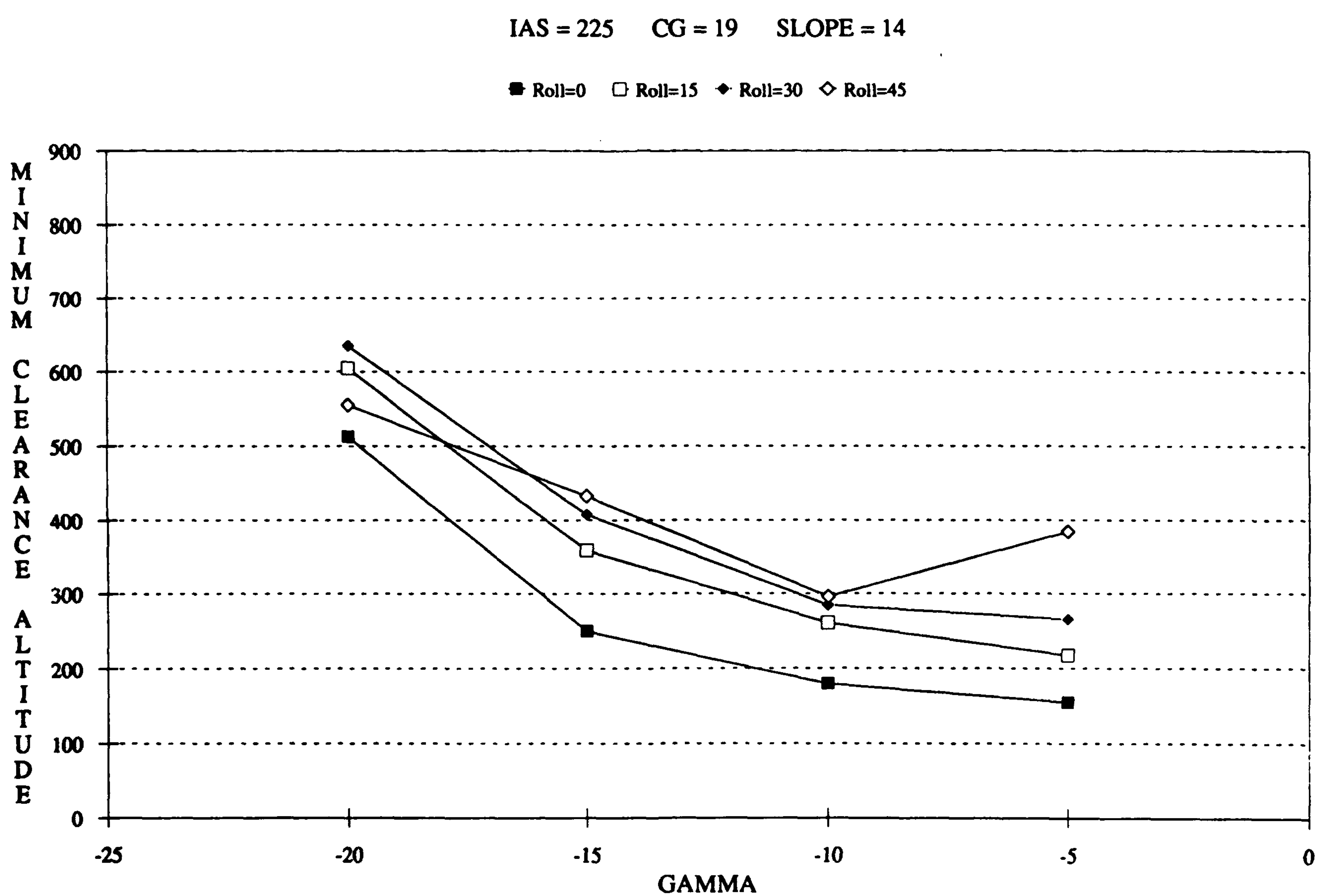


Figure 59. Minimum clearance as a function of gamma for pilot model: IAS=325, Cg=19, & Slope=14.

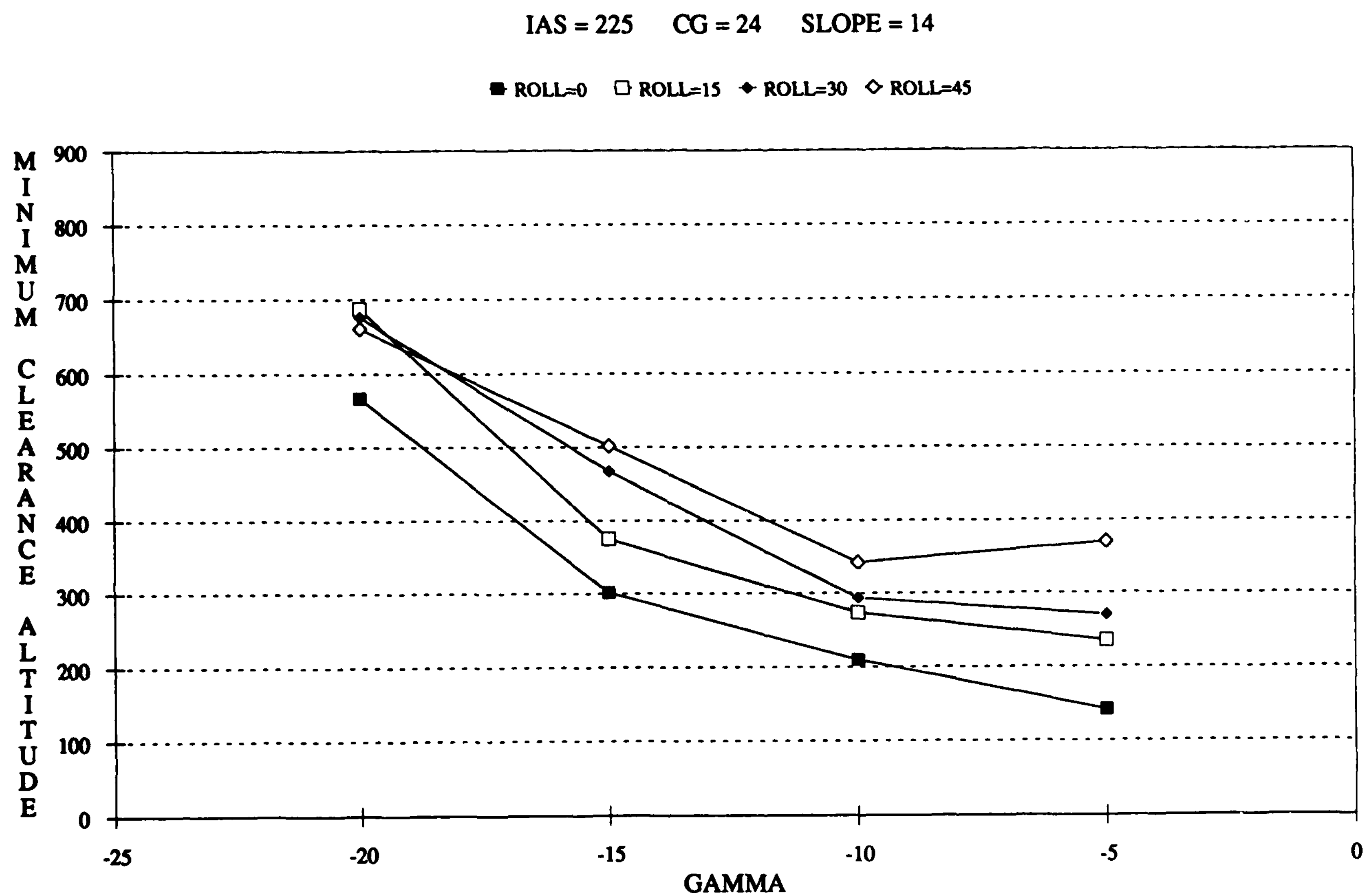


Figure 60. Minimum clearance as a function of gamma for pilot model: IAS=225, Cg=24, & Slope=14.

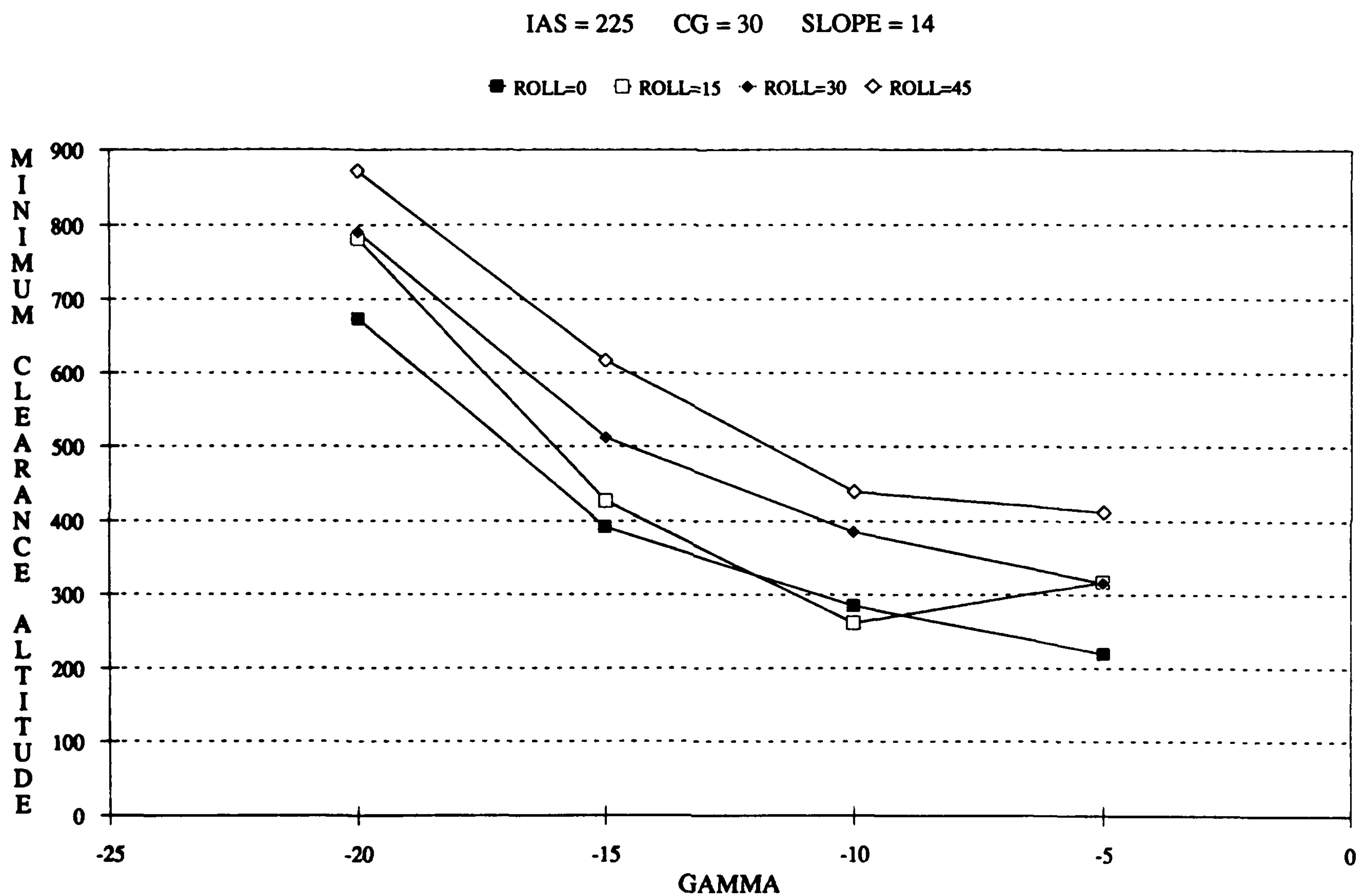


Figure 61. Minimum clearance as a function of gamma for pilot model: IAS=225, CG=30, & Slope=14.

Phase II Discussion

The Phase II Evaluation employed a pilot model to test the ability and consistency in predicting required altitude as the algorithm changed paths. During Part 1 of our Phase II evaluation, we concluded the algorithm did not adequately account for the effects of terrain slope. This failure was evidenced by the numerous ground collisions experienced by the robot pilot model during its recovery procedure. Generally, the results found during Part 1 confirmed the findings from Phase I, the algorithm's inability to accurately account for the effects of terrain slope. These findings were then forwarded to Cubic and the revised algorithm was evaluated in Part 2.

It was determined in Part 2 that the algorithm had improved in its ability to provide adequate minimum clearance. This became quite apparent when no ground impacts occurred during the Part 2 data runs. Additionally, trend analysis and graph comparisons revealed that all of the gamma, roll, airspeed, and terrain slope variables caused the expected effects in minimum clearance altitudes. By reviewing the mean minimum clearances for Part 2 (Table 4), one finds the hypothesized pattern of results for all four independent variables. Terrain slope results were greatly improved, as evidenced by a complete reversal in the order of the means from Part 1 (original algorithm) to Part 2 (revised algorithm). Additionally, comparisons of the standard deviations from Part 1 with the Part 2 standard deviations reveal the variability in the minimum clearances for each of the independent variables decreased. Only the terrain slope standard deviations remained relatively constant. These findings indicated the revised algorithm (Part 2) had been greatly improved.

One concern did arise from the Part 2 portion of our Phase II evaluation. The effects of Cg were not accounted for by the algorithm. Our findings indicated Cg did have an effect on the minimum clearance, and consequently, should be considered in the design of the GCAS algorithm. This finding also supported our Phase I finding that the effects of Cg should be considered. However, a potential problem does exist with the incorporation of Cg. At present, the KC-135 aircraft does not have a sensor that detects Cg. Therefore, some sensor would need to be installed in the KC-135 aircraft to allow the algorithm to account for the effects of Cg. This might prove to be cost prohibitive. Prior to the Phase III and Phase IV evaluations, Cubic made no further corrections to their algorithm.

PHASE III

The objective of the third phase of the evaluation was to introduce the pilot factor and replicate a subset of the runs flown by the robot pilot model throughout Phase II, with an increased emphasis on standard flying configurations. Phase III allowed C/EC/KC-135 pilots to fly a GCAS equipped KC-135 simulator in order to evaluate and critique the most current version of the GCAS algorithm. The critique, as well as the performance and subjective results, was in turn shared with the SPO and the designers (Cubic Defense Systems) for modification of the algorithm. Phase III was also broken into two parts. During Part 1, pilots flew a subset of the dive configuration runs performed during Phase II. For Part 2, pilots flew eight ILS approaches and the resulting data were analyzed to determine the predictive accuracy of the GCASLAND subroutine.

Method

Subjects

A total of nine pilots (eight males and one female) rated in the C/EC/KC-135 were used. Due to the state of world affairs at the time, only three of the subjects were operational pilots current in the aircraft. The remaining six were chosen from a list of volunteers from the various offices located at Wright-Patterson AFB, Ohio. The pilot's were required to have been an aircraft commander in the KC-135. The resulting personal data indicated the subject pool was relatively older (x=31.98), more experienced (average total flight hours=2819 and average total KC-135 flight hours=1739), but less current in the aircraft (average time in months since last flight =25) than the current operational force.

Apparatus

Facility. Refer to the Phase II Apparatus section for a description.

Computer Complex. Refer to the Phase II Apparatus section for a description.

Simulator. Refer to the Phase II Apparatus section for a description of the KC-135 simulator. Additionally, a console located behind the pilot's seat allowed the experimenter to remain in the cockpit during training to provide the pilot with needed hands-on demonstrations and explanations. The decision height lights and warning horn were disabled to keep the pilot from anticipating a possible GCAS warning.

Experimenter's Console. The experimenter's console was located approximately 10 feet away for the simulator. It included a complete intercom system, with communication to and from the pilot inside the simulator. The console's displays duplicated the simulator's instruments and displays, and were used to monitor the pilot and aircraft performance. Furthermore, the console's controls permitted the experimenter to start, stop, and reset the simulation at any time.

Voice Message Unit Mechanization. One warning and three caution voice messages were presented to the pilot's headset through the intercom channel. The messages were "Pull-up," "Flaps," "Gear," and "Glideslope." The pilots were allowed to set the volume level of the interphone as they saw fit. The warning message was mechanized in accordance with the Cubic algorithm. This dictated the warning be presented once, then inhibited for a five-second period. At the end of the five-second period, the warning would only be repeated if the aircraft was still in a warning condition. The "Pull-up " message was presented in pairs ("Pull-up/Pull-up") with an inter-message

interval of 500 milliseconds. The "Flaps," "Gear," and "Glideslope" messages were presented once each for the given condition and then inhibited for the five-second period.

Audio Systems. The voice messages were recorded on an Amiga micro computer by a female employee of the CSEF. The employee, who had a distinctive and mature mid-western voice, presented the messages in a formal and impersonal manner. The Amiga used a high speed voice digitizer (Future Sounds), with a sampling rate of 10,000 samples per second, to convert the messages from analog to digital format. The Amiga was, thereafter, connected to the main frame computers using an RS-232 interface, and transmitted the messages to the pilot's headset (an ASTROCOM model number 20680 with MX-2508/A/C pads) through the intercom channel.

Visual Warning Signal. A flashing red light placed fifteen degrees right of the center field of view and just to the left of the engine and fuel instrument panels provided the visual warning stimulus. The word "Altitude" was etched in black lettering on a red background. This type of light and nomenclature was chosen based on the results of an earlier GCAS questionnaire (Rueb & Hassoun, 1990).

Part 1 - Dive Configuration

Design

Phase III of the evaluation was designed to compare C/EC/KC-135 pilots' performance and subjective data as a function of four independent variables. These variables were: (1) terrain slope, (2) indicated airspeed, (3) roll angle (both left and right to avoid response biases), and (4) flight path angle (gamma). Table 5 presents the levels for each of the independent variables. The four independent variables were recorded at the time of warning initiation.

Table 5. Phase III: Pilot-in-the-loop independent variables.

ROLL	GAMMA	IAS	SLOPE
15	-5	225	7
30	-10	325	14
	-15		

The actual condition of the aircraft and the total altitude loss estimated by each of the subroutines were recorded for each of the data runs. Three dependent measures of interest were also recorded for subsequent data analysis. These were maximum G's, minimum clearance altitude, and total altitude lost. Maximum G's represented the highest instantaneous g-force placed on the aircraft, and acted as one of our criteria for accepting or rejecting a given run. If a run exceeded 2.5 g's, then the run was discarded and a new run performed. This value was chosen as it represented the midpoint between the operational limit (2.0) and the structural limit (3.0) of the aircraft.

Total altitude lost allowed the comparison of the actual total altitude loss with the algorithm's predicted total altitude loss. The minimum clearance altitude, defined as the minimum distance between the aircraft and the ground (feet-AGL) during the aircraft's recovery, was the primary dependent variable of interest. This variable provided the experimenter with the information needed to determine if the algorithm had provided adequate ground clearance. The overall experimental design was a repeated measures design for which each pilot was required to fly each of the 24 different run conditions (2 Roll x 3 Gamma x 2 IAS x 2 Slope). All runs were successfully completed.

Procedure

The pilot was given a standardized briefing explaining the background for the study, the simulator's capabilities and peculiarities, and the particular flight profiles they would be required to fly. Upon completion of the briefing, the pilot was provided instruction on the simulator GCAS warning and on the various locations of the aircraft controls. The pilot was then allowed to fly the aircraft simulator until they felt comfortable with their ability to fly the simulator proficiently. In all cases, the pilot felt comfortable enough with his/her ability to fly the simulator proficiently within two hours of beginning the training period. At that time, the pilot began the Part 1 portion of the Phase III evaluation.

Part I required the pilot to perform a subset (See Table 5) of the dive configuration runs performed during Phase II of our evaluation. This portion of the evaluation simulated flying in the weather without an outside window visual scene. In an attempt to decrease pilot reaction time performance biases (i.e., possibility of the pilot accurately anticipating the warning), the simulator was initially frozen at an altitude between 1000-5000 feet above the estimated warning altitude. Prior to the release of the KC-135 simulator, the pilot was given the desired aircraft parameters (Roll angle, IAS, and Gamma) for each particular dive configuration trial. The experimenter completed this exchange with a "Ready when you are" statement. The pilot then adjusted his stab trim and responded "Ready" when he/she was prepared for simulator release.

A set-up control interface program developed to simplify user-computer interaction allowed the experimenter to monitor real-time characteristics of the simulator as it flew each configuration. Table 6 presents an example of the computer program page that the experimenter used to manipulate the terrain the simulator flew over, in addition to a list of the desired parameters for that trial.

Table 6. An example of the pilot-in-the-loop set-up page.

RECORD GCAS DIVE RUNS

1. TRIAL #	: 24	A. INCREMENT RUN	: ON
2. SUBJECT #	: 9	B. QUICK LOOK	: ON
3. ROLL ANGLE	: 9	C. DATA COL	: ON
4. GAMMA	: -15.		
5. AIR SPEED	: 275.		
6. TERRAIN SLOPE	: 14.		
7. BUFFER ELEV	: 1000.		
8. ALTITUDE	: 6000.		

PRESS 'R' TO RUN

Upon release, the pilot was required to maintain the actual roll angle and gamma of the simulator within 2.5 degrees of the desired parameters until warning initiation. Failure to be within 2.5 degrees of the desired roll angle or gamma parameters at warning initiation or failure to keep the maximum g's of the aircraft below 2.5 (see Design section) during recovery would require that trial to be rerun. No criteria were established for the indicated airspeed parameter, because pilots were limited as to what they could do to maintain

airspeed in a steep (15°) dive condition, especially under the low (225 knot) airspeed condition. The experimenter monitored real time simulator performance characteristics using the data page exhibited in Table 3.

At warning initiation, the pilot was required to recover the simulator as quickly as possible within the operational limitation of the aircraft. The pilot was informed to continue the recovery until a positive ground clearance rate of climb was established on the radar altimeter. When a positive radar altimeter rate was established, the experimenter terminated the trial. Upon termination, the experimenter used a "quick-look results" display generated on the experimenter's console (Table 7) to inform the pilot of the actual dive angle, roll angle, and downward vertical velocity at warning initiation, in addition to the minimum clearance altitude reached during recovery. The pilot was then required to make the following subjective rating: "In your opinion, was the ground clearance provided by the GCAS for your last run: Too high, slightly high, about right, slightly low, or too low."

Table 7. An example of the pilot-in-the-loop quick-look results display.

GET GCAS EVALUATION

INITIAL BA	5.	WARN ALT	1325.46	BANK ANGLE	4.593
INITIAL DA	-15.	MIN CLR	1000.00	DIVE ANGLE	-9.78
INITIAL AS	225	ALT LOST	325.46	AIR SPEED	248.795
		MAX G'S	1.748	VZ	-1223.32

1. TOO HIGH
2. SLIGHTLY HIGH
3. ABOUT RIGHT
4. SLIGHTLY LOW
5. TOO LOW

Enter evaluation (RETURN TO EXIT):

The evaluation number was entered onto the screen and then recorded as part of the overall trial. This information was later used to develop the pilot window of acceptability (discussed later). Each pilot flew 24 dive configuration trials. The order of trial presentation was randomized to avoid task order effects.

Part 1 Results

The same variables collected for Phase 2 were collected for the Part 1 portion of Phase III. These variables were predicted altitude loss due to GCASALRT, GCASDIVE, GCASROLL, and SAFTHR; roll, gamma, airspeed, aircraft g's, and terrain slope at warning initiation; and total altitude lost and minimum clearance during the ensuing recovery. One additional variable, the pilot's minimum clearance rating, was also collected. Unlike Phase 2, formal statistical analyses were possible, since the data represented that of nine individual pilot subjects, rather than just one subject (robot pilot). Consequently, the data were not only analyzed for trend information, but were also subjected to multiple regression analyses.

A mean minimum clearance was computed across all nine pilots for each of the 24 dive configuration trials. The resulting means were then sorted by indicated airspeed and

terrain slope and graphed as a function of flight path angle (gamma) for all the roll angle conditions. An inspection of the graphs (Figures 62-65) with each other provided the information needed to determine the algorithm's ability to provide adequate minimum clearance.

Airspeed Effects

A comparison of Figure 62 with Figure 63 and Figure 64 with Figure 65 indicates airspeed generally resulted in higher minimum clearances. However, a repeated measures analysis of variance (see Table 8) revealed airspeed only affected minimum clearance through its interaction with the three other independent variables (gamma, roll, and slope). This could be the result of the pilots limited ability to control airspeed during the dive configuration runs. Consequently, the wide range of airspeed for the two airspeed levels represented more of a continuous variable than that of a discrete variable.

In each case, the interaction was caused by a decrease in the mean minimum clearance as airspeed increased from 225 to 325. T-tests between the minimum clearance means for the gamma-airspeed (t = .5487), roll-airspeed (t = .0455), and slope-airspeed (t = .0842) interactions resulted in nonsignificant findings at the .05 α-level. This indicates the interactions were caused by means not found to be significantly different from each other. Given the mean minimum clearances were generally in the hypothesized direction and that the continuous airspeed variable was forced into a dichotomous variable, it appeared airspeed was adequately accounted for by the Cubic algorithm.

Table 8. Repeated measures analysis of variance summary table.

Source	df	SS	F	p
Gamma (G)	2	7336869	43.02	.0001**
Roll (R)	1	1599432	47.24	.0001**
Speed (Sp)	1	291347	2.08	.1876
Slope (Sl)	1	559392	3.66	.0923
G*R	2	105963	1.06	.3701
G*Sp	2	460731	6.14	.0105**
G*Sl	2	378010	5.50	.0157**
R*Sp	1	327185	6.65	.0327**
R*Sl	1	16093	.29	.6077
Sl*Sp	1	339146	5.49	.0407**
G*R*Sp	2	0	.00	.9999
G*R*Sl	2	41171	.54	.5925
R*Sp*Sl	1	0	.00	.9999
G*R*Sp*Sl	2	76174	1.10	.3577

**Significant at the .05 α-level.

Roll Angle Effects

A review of Figures 62-65 and Table 8 reveals roll angle had the hypothesized effect on minimum clearance. The roll angle effect was found to be significant (p=.0001). Additionally, no interactions other than that explained above occurred. Accordingly, we concluded the effects of roll angle are adequately incorporated into the algorithm.

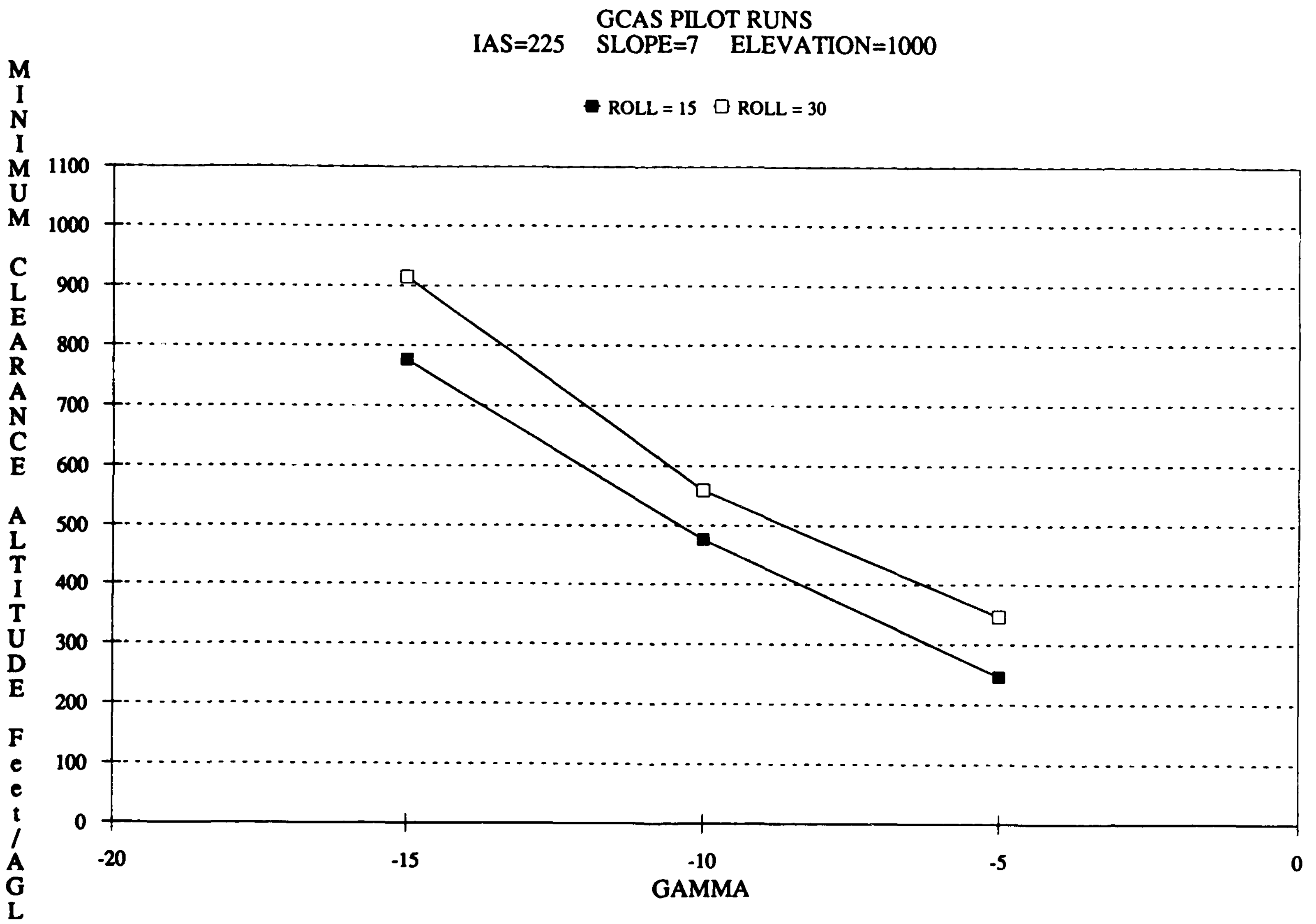


Figure 62. Mean minimum clearance as a function of gamma for nine pilots: IAS=225, Slope=7, and Elevation=1000.

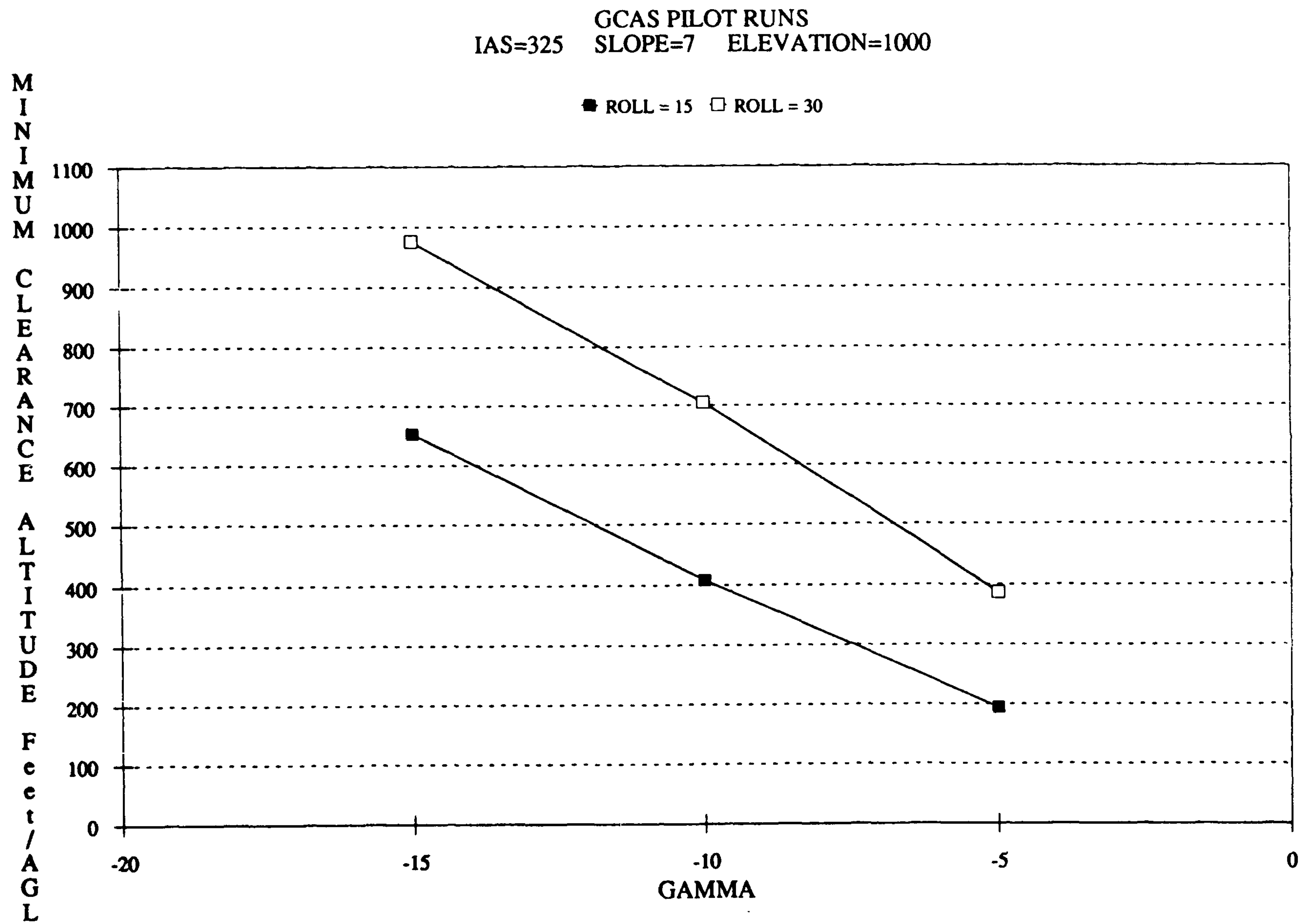


Figure 63. Mean minimum clearance as a function of gamma for nine pilots: IAS=325, Slope=7, & Elevation=1000.

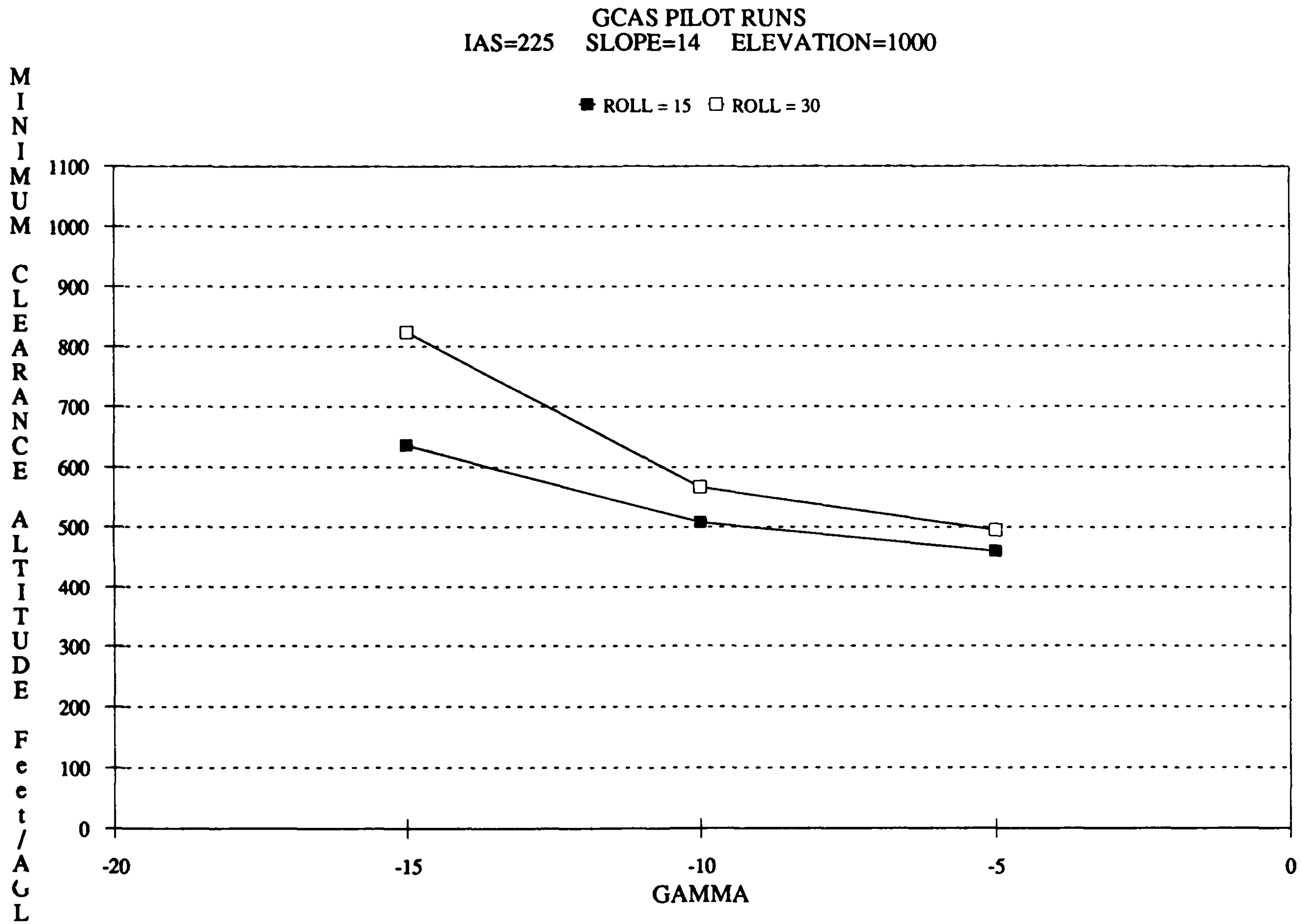


Figure 64. Mean minimum clearance as a function of gamma for nine pilots: IAS=225, Slope=14, and Elevation=1000.

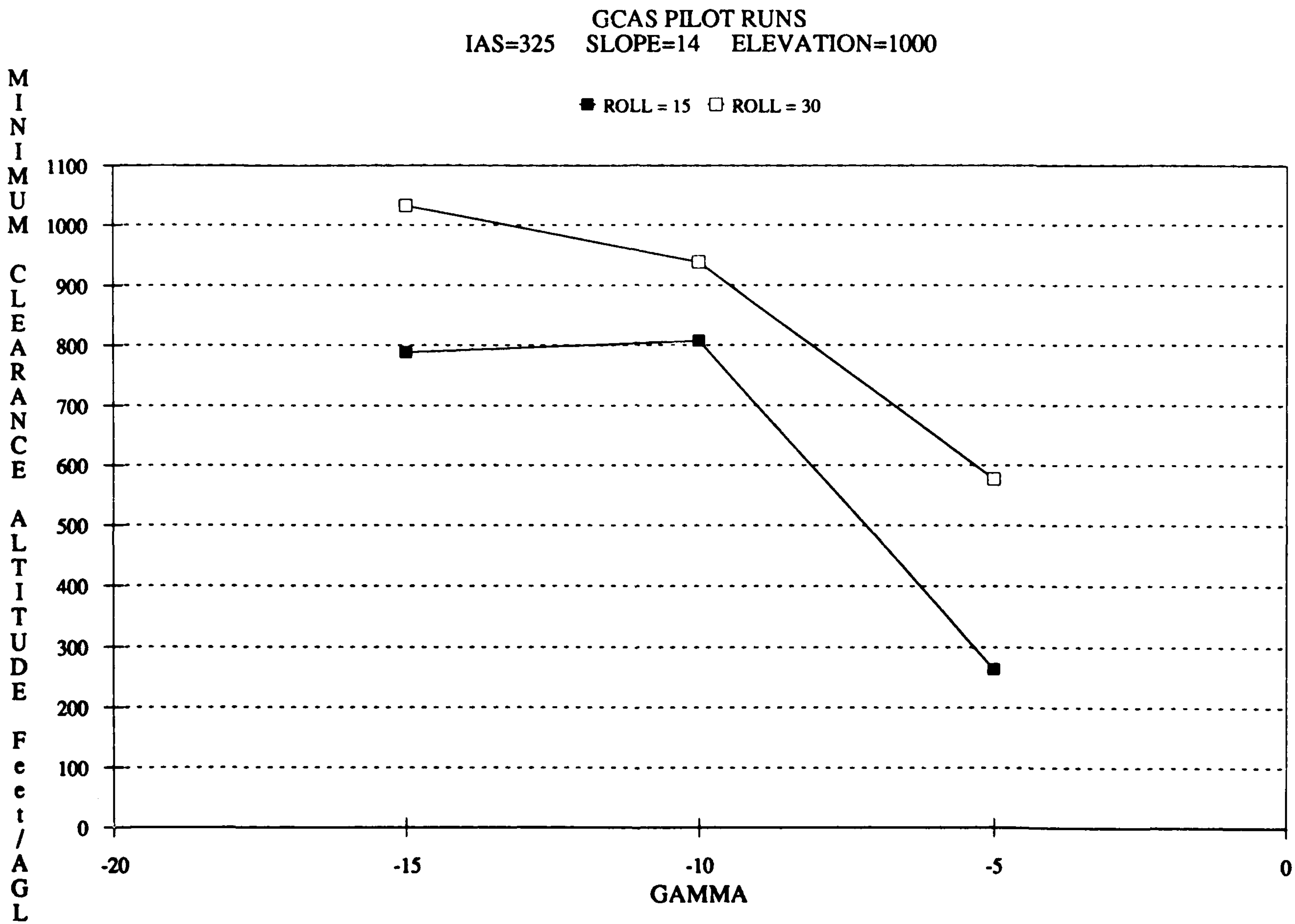


Figure 65. Mean minimum clearance as a function of gamma for nine pilots: IAS=325, Slope-14, and Elevation=1000.

Flight Path Angle Effects

A review of Figures 62-65 reveals that gamma effects provided the expected results. Mean minimum clearance decreased as gamma decreased. This effect was found to be statistically significant (p=.0001). Gamma, however, was involved in two different two-way interactions. The first interaction with airspeed was explained previously. The interaction with slope will be explained later. Given the general effect of gamma was as expected and later analyses indicated slope was the cause of the interaction, we concluded gamma was adequately considered by the Cubic algorithm for the flight path angle range of -5^{o} to -15^{o}.

Terrain Slope Effects

Comparisons of Figure 62 with 64 and Figure 63 with 65 provide trend information indicating increases in slope resulted in increases in minimum clearances. This was expected. However, the effect of slope on minimum clearance altitude was not significant (p=.0923). Additionally, slope was involved in an unexplainable interaction with gamma. Later analyses revealed slope was not adequately computed by the algorithm.

Pilot Window of Acceptability

Pilots' rating data were divided into five separate data sets and analyzed independently using the linear regression analysis technique. Minimum clearance altitude was considered the main dependent variable, while vertical velocity (which included two critical factors: airspeed and flight path angle) was considered the main independent variable. The five ratings corresponded to the statements found in Table 9. The regression analysis described the relationship between minimum clearance altitude as a function of vertical velocity for each of the ratings, by calculating the correlation coefficient and the function of each line.

Table 9. Rating criteria for each minimum clearance altitude.

MINIMUM CLEARANCE ALTITUDE

1. TOO HIGH
2. SLIGHTLY HIGH
3. ABOUT RIGHT
4. SLIGHTLY LOW
5. TOO LOW

Figures 66-70 are examples of the actual runs performed by the various pilots. There is an example for each rating. For a description of the graph information, refer to the Figure 29 discussion found in the Phase II results section. One additional variable was added to the bottom of the right-hand column. This is the rating (EVAL NUM) that the pilot chose for the given run. Additionally, a minus sign was added to the roll value when the initial condition was a left bank condition. The figures provide an idea of how the pilots flew the aircraft. A comparison of Figure 66 with 67 supports our contention that as vertical velocity increases, pilots prefer increases in minimum clearance altitudes. The minimum clearance of 1483 feet (Figure 66) was rated "Too high" for a vertical velocity of 3038 feet per minute; whereas, the same pilot rated a minimum clearance of 1357 feet as only "slightly high" for a vertical velocity of 8886 feet per minute.

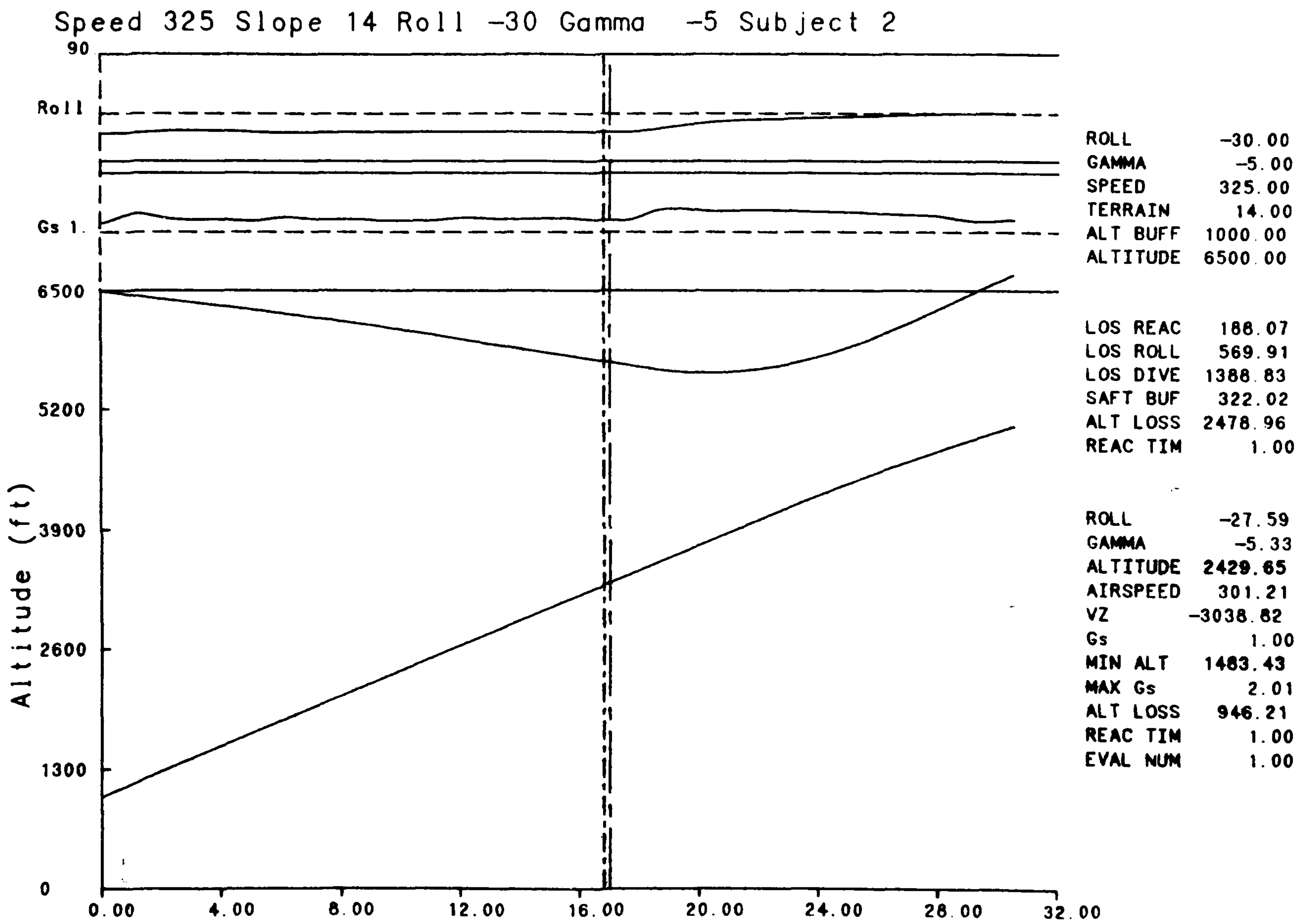


Figure 66. Graph of a dive configuration trial for a subjective rating of 1.

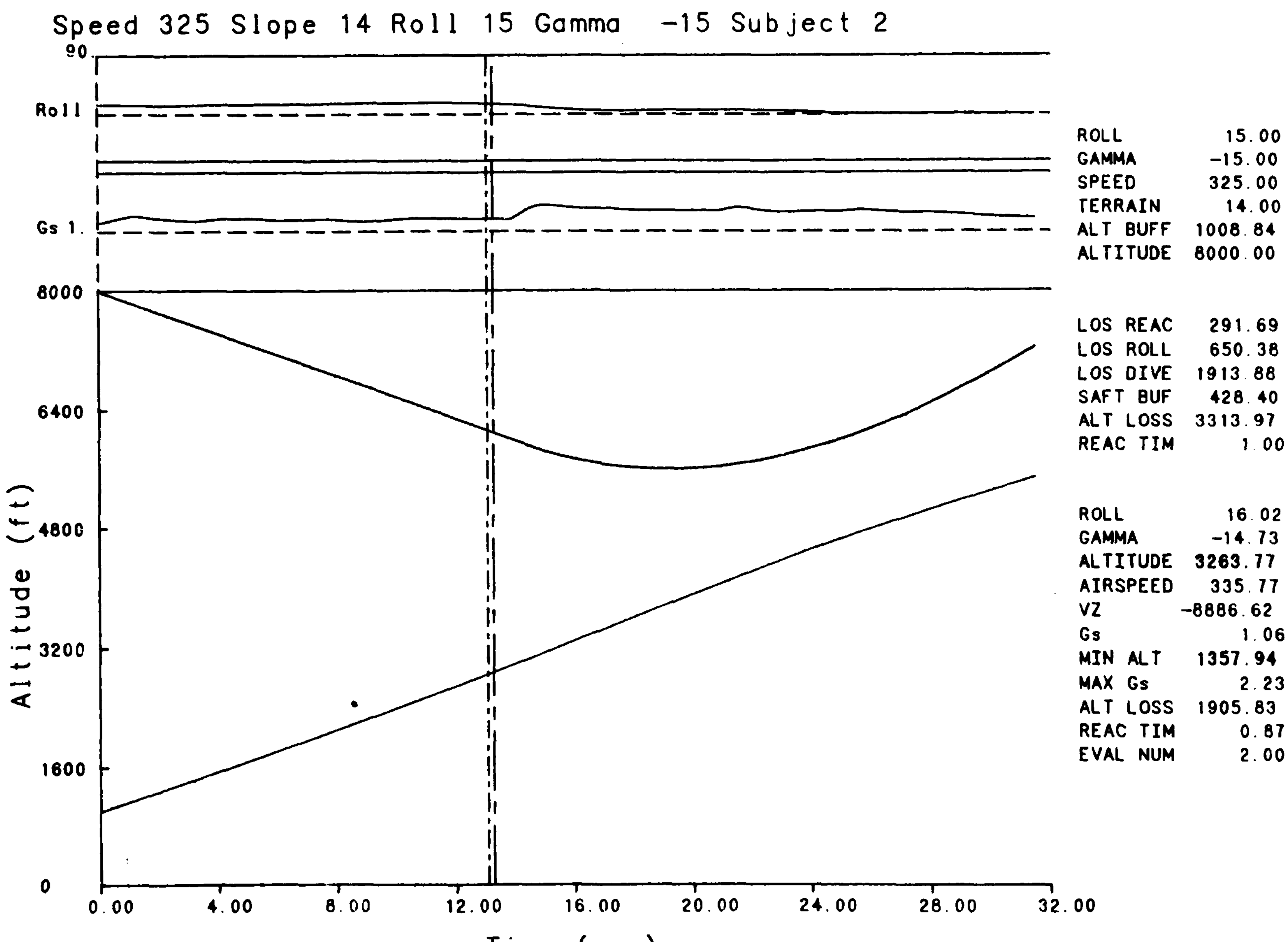


Figure 67. Graph of a dive configuration trial for a subjective rating of 2.

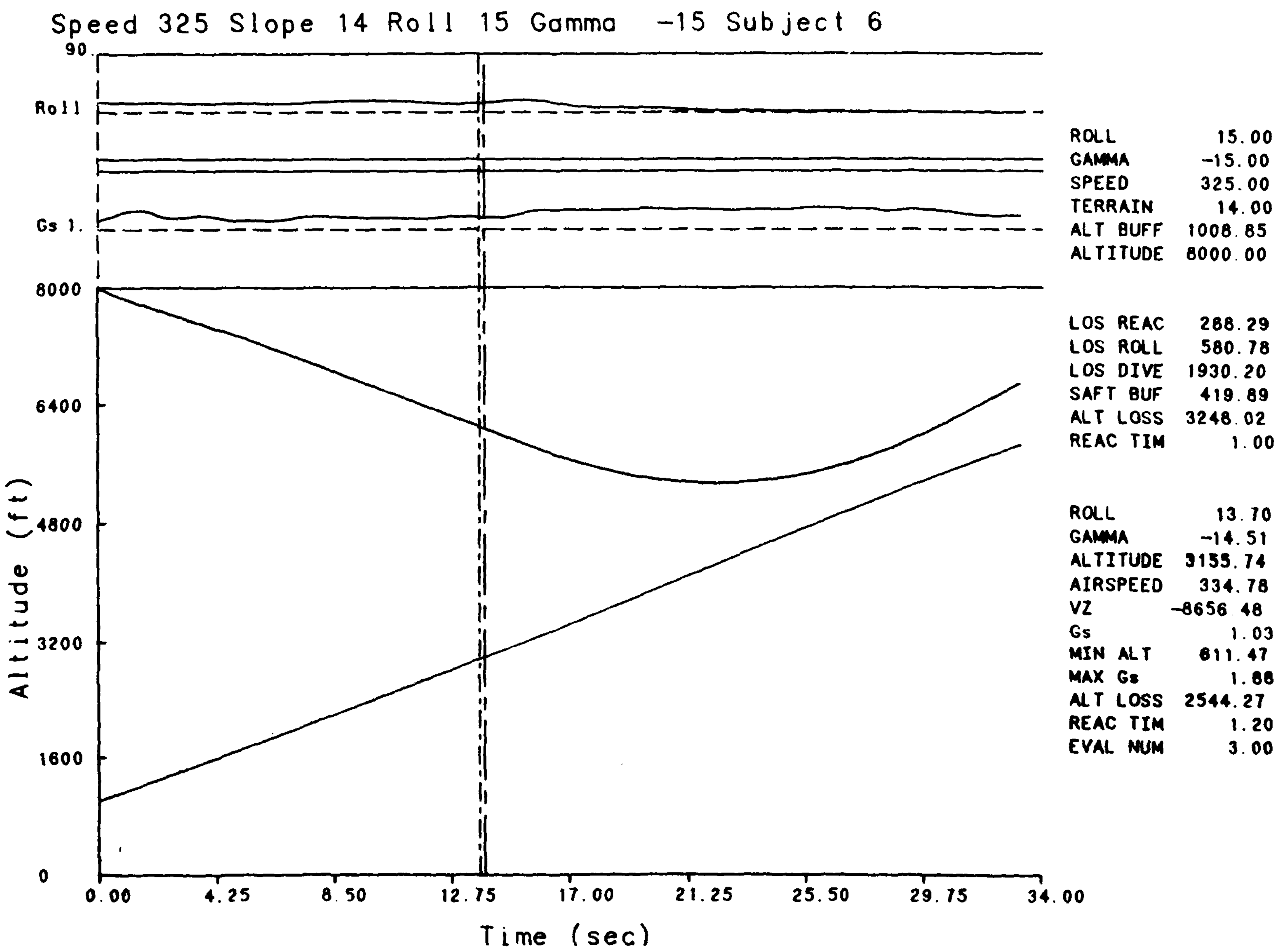


Figure 68. Graph of a dive configuration trial for a subjective rating of 3.

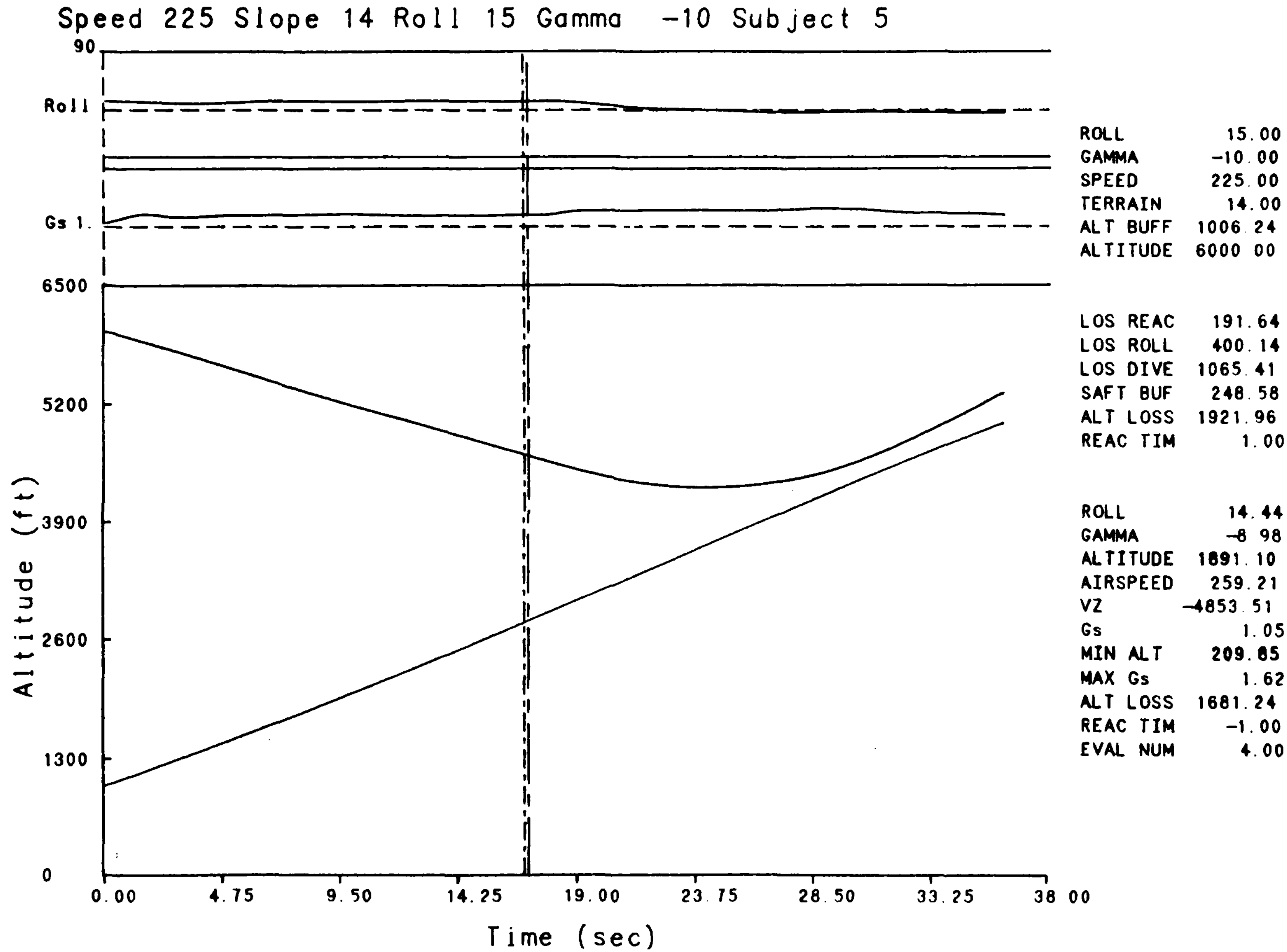


Figure 69. Graph of a dive configuration trial for a subjective rating of 4.

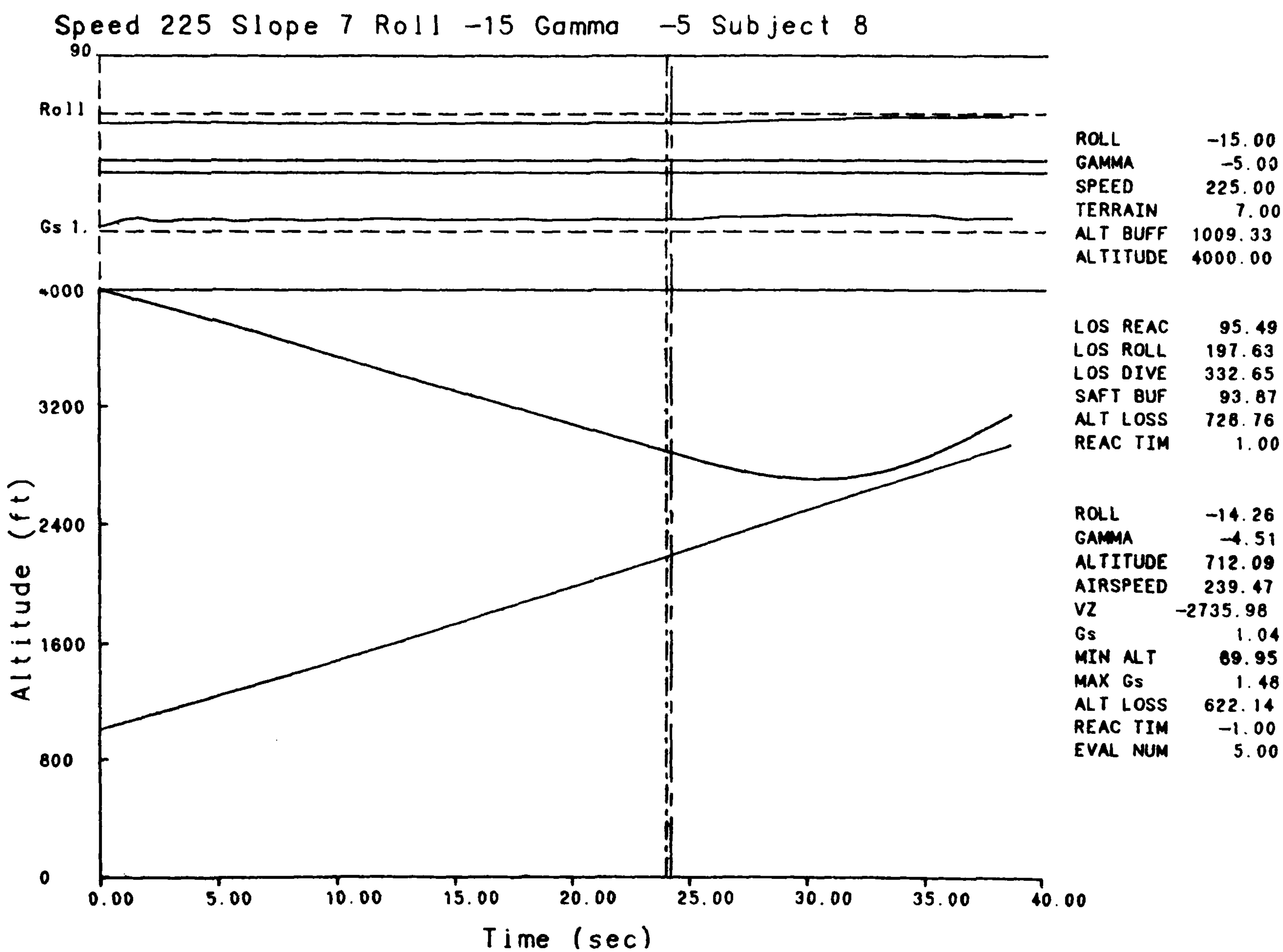


Figure 70. Graph of a dive configuration trial for a subjective rating of 5.

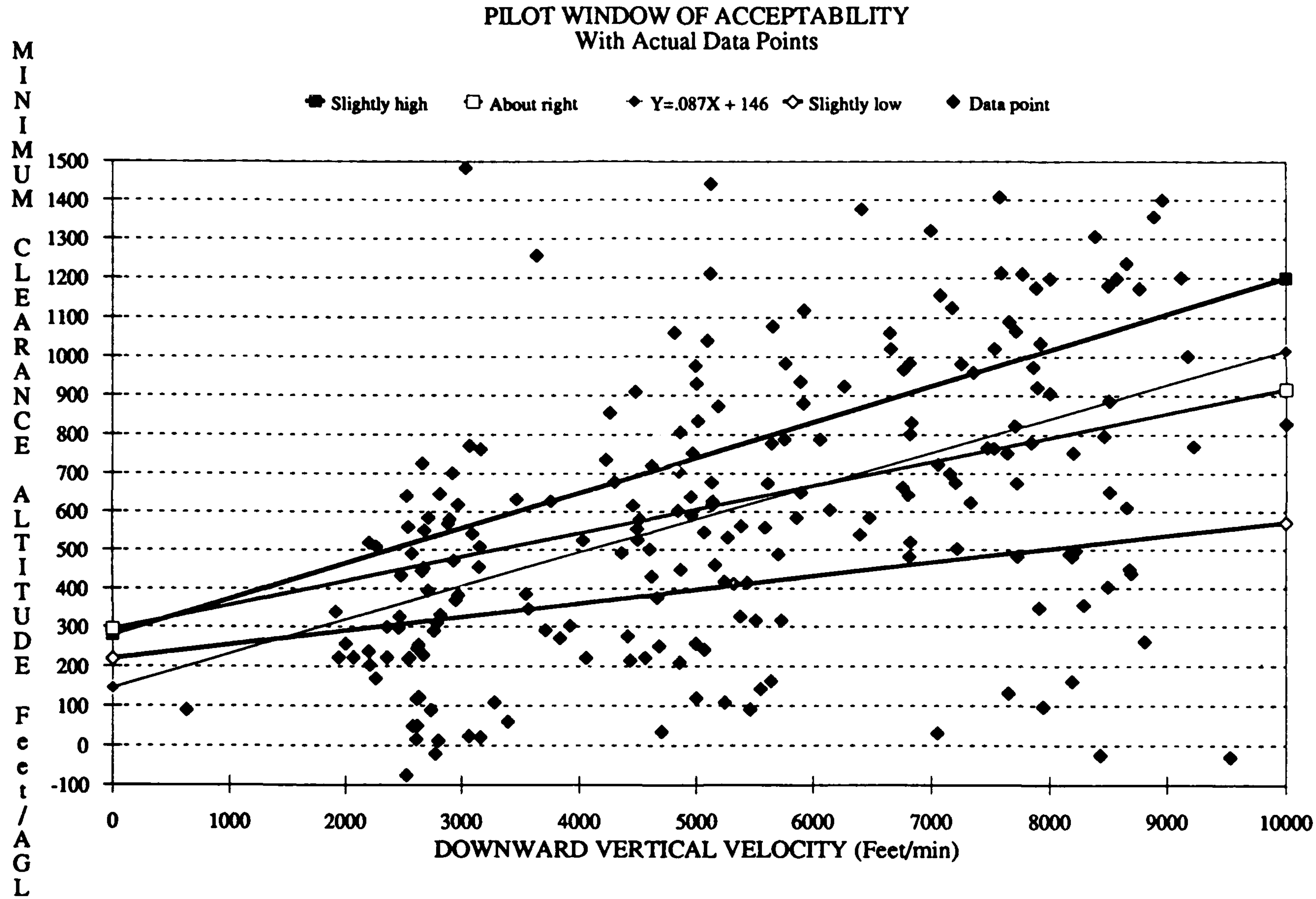


Figure 71. Pilot window of acceptability with regression lines for ratings 2, 3, & 4 and for total data set.

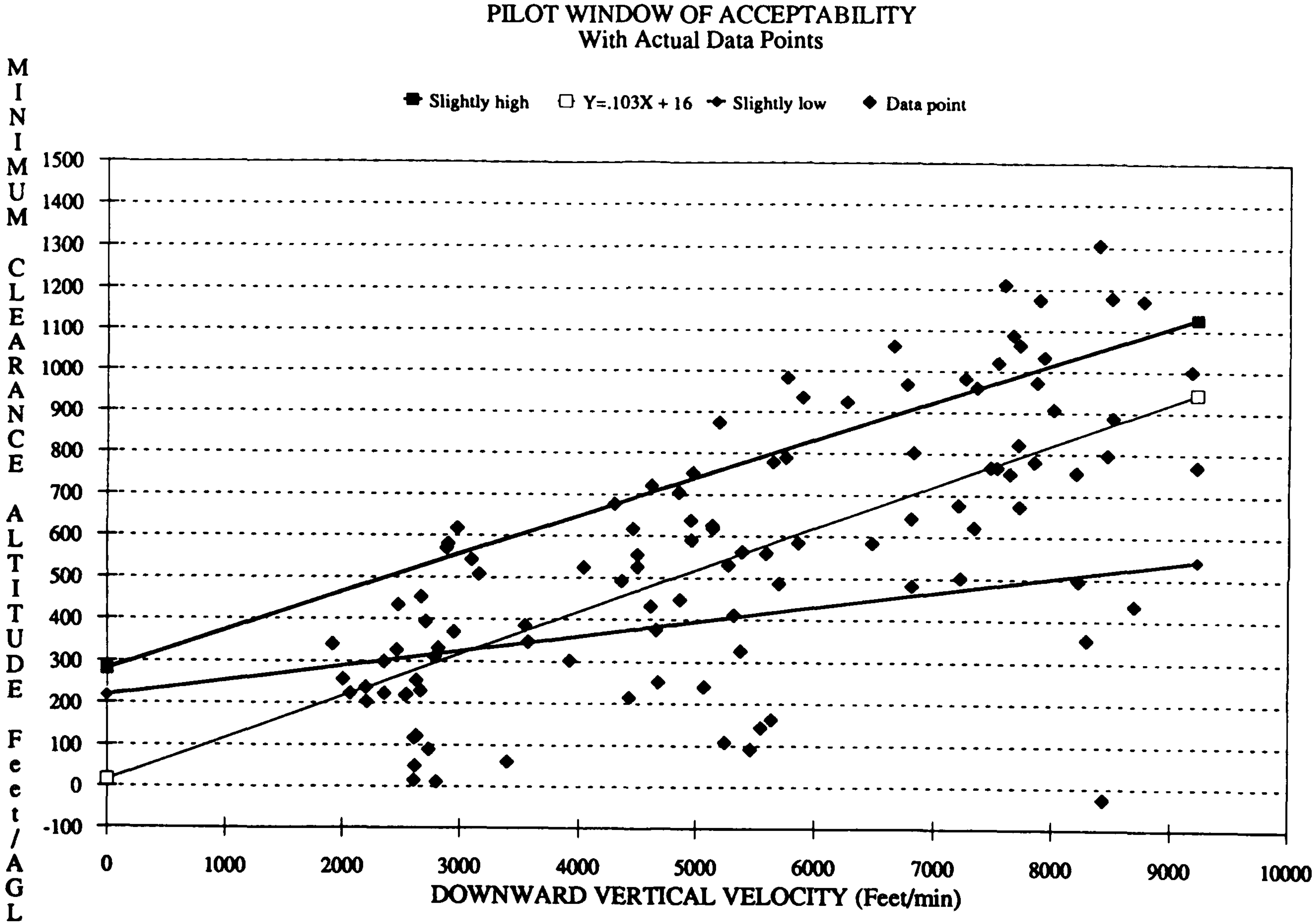


Figure 72. Pilot window of acceptability for a terrain slope=7.

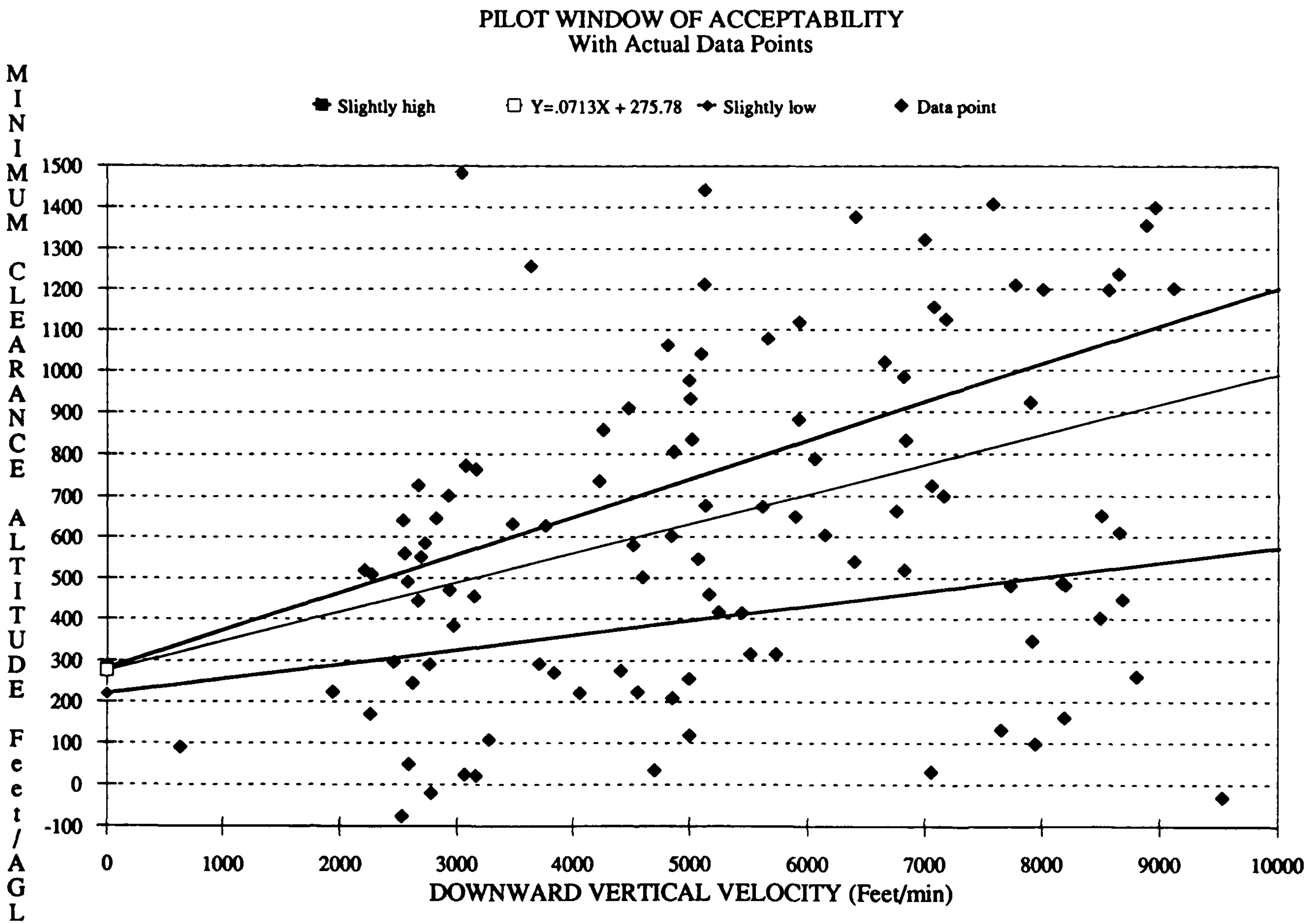


Figure 73. Pilot window of acceptability for terrain slope=14.

Figure 71 displays all of the 216 data points and each of the regression lines for the ratings of 2, 3, and 4. The figure also displays the overall line of prediction of the Cubic algorithm. To provide a graph of adequate size, four data points were not shown. Three of these data points represented minimum clearances greater than 1500 feet and the remaining data point represented a very high dive rate (11,000 ft/min) for the KC-135 aircraft. However, these data points were included in the appropriate regression analyses.

The upper limit of the window of acceptability was determined by regressing the minimum clearance altitudes onto the vertical velocity for all trials given a rating of 2 (slightly high). The lower limit of the window was calculated in a similar manner for a rating of 4 (slightly low). The regression line for the rating of 3 indicates what the pilots felt was the appropriate regression line of prediction (Y=.0623X + 293). The overall line of prediction is the regression line for every trial (N=216) and is represented by the equation Y=.087X + 146. It is the Cubic algorithm line of prediction. The resulting regression line for the upper limit was Y=.0919X + 280; the lower limit, Y=.0353X + 219. All the regression lines were analyzed for higher order trends. Linear models proved to be the most appropriate models for all of the data sets.

The "window of acceptability" is the area located between the slightly high and the slightly low regression lines and represents the region that pilots feel relatively comfortable with the minimum clearance provided by the algorithm for the given vertical velocity. Minimum clearance altitudes greater than the upper limit would be considered too high (false alarms). Minimum clearances below the lower limit would be considered too low (unsafe-too close for comfort). As Figure 71 shows, the variability of the minimum clearances provided by the algorithm was excessive. Thirty-one percent of all of the minimum clearances were false alarms. Thirty-one percent of the minimum clearances were "too close for comfort." Only thirty-eight percent of the actual minimum clearances provided were within the window of acceptability.

To determine the source of this variability, the pilot window of acceptability was analyzed as a function of slope. Figures 72 and 73 are examples of the pilot window of acceptability with only the data points for the given slope condition plotted. A decrease in the variability is observed for a slope of seven (Figure 72). Fifty-two percent of the data fell within the window of acceptability. Only 20% of the data points were false alarms, while 28% were "too close for comfort." This is an improvement over the entire data set. On the other hand, the variability of the data set for a slope of 14 (Figure 73) actually increased in comparison to the the total data set. Only 26% of these data points fell within the pilot window of acceptability. The false alarm rate was 42% and the "too close for comfort" rate was 32%.

Part 1 Discussion

The statistical analyses and trend analyses for Part 1 indicated the inability of the Cubic algorithm to provide consistent, adequate minimum clearances for the KC-135. The algorithm was only able to provide a pilot-acceptable minimum clearance 38% of the time. The algorithm generated minimum clearances considered too close for comfort 31% of the time. Four of these resulted in ground collisions. The false alarm rate was also 31%.

The follow-on analysis for slope effects revealed the algorithm's inability to accurately account for the effects of slope caused increased variability in the minimum clearance altitudes. Given the above results, it is highly questionable whether the pilot would place any confidence in this algorithm. The Cubic algorithm needs to improve its ability to accurately account for the effects of slope given various aircraft configurations.

Part 2 - Approach and Landing

Procedure

Upon completion of the Part 1 dive configuration trials, the pilot was given a short rest period. The pilot was then given an indepth briefing describing the ILS approach to be performed. Prior to the actual recording of any data the pilot was allowed to practice as many ILS approaches as desired. The practice period was terminated when the pilot felt comfortable in his/her ability to fly the ILS approach proficiently.

The pilot was required to fly an ILS approach to Runway 24R at Los Angeles (Figure 74). All radios and ILS frequencies were preset prior to the start of each run. The KC-135 simulator was positioned at a starting point 14 NM Northeast of the runway at an altitude of 2000 feet. This required the pilot to intercept both the glideslope and localizer course. The Night Visual System described earlier was active; however, simulated weather prevented the pilot from identifying the runway lights until a descent below 300 feet was made. This forced the pilot to use the instruments displaying ILS information and prevented him from using outside visual cues during the approach. The pilots flew a total of eight approaches for the various aircraft configurations of flaps (up or down), gear (up or down), and forced glideslope deviations (yes or no).

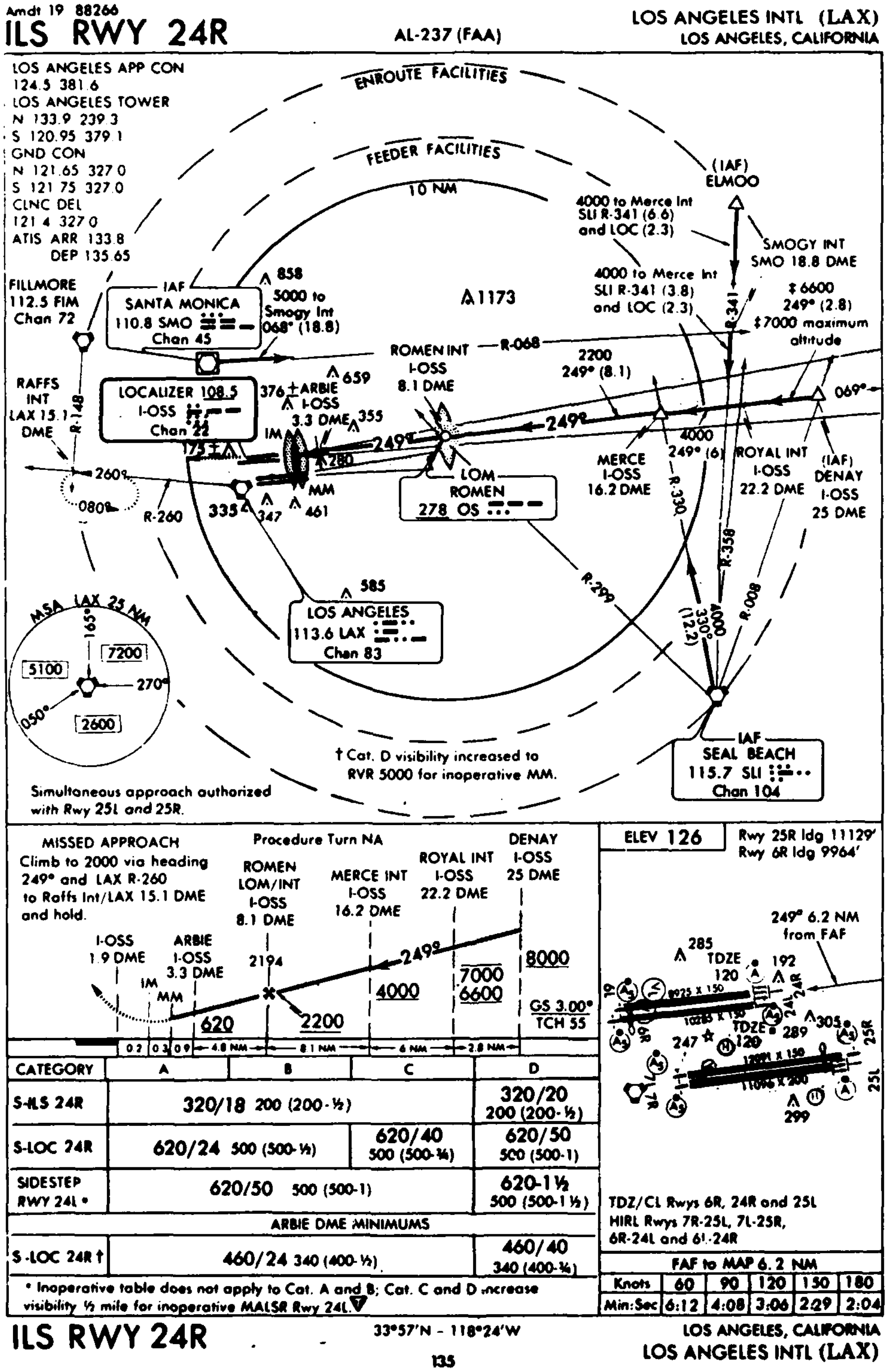
Data Collection

Data collection for the ILS approach was started at glideslope intercept or at 1000 feet (AGL), whichever occurred first. It continued on a 30 Hz cycle until 100 feet (AGL). The data set used for analysis was based on individual data points recorded every fifteen seconds, and for every crash and warning. The recorded information formed the general categories: algorithm's calculations, and actual aircraft conditions. The algorithm calculation variables were: warning (yes or no), time of data recording, reaction time (ft), roll (ft), gamma (ft), safety buffer (ft), total altitude loss (ft), and pilot reaction time (sec). The actual aircraft conditions were: roll (degrees), gamma (degrees), altitude (ft-AGL), airspeed (knots), vertical velocity (ft/min), terrain slope (degrees), minimum clearances (ft-AGL), Maximum G's, total altitude lost (ft), pilot reaction time (sec), and G's. The period 30 seconds before until 60 seconds after the warning defined the data collection window.

Part 2 Results

The resulting data set consisted of 309 data points. These data were individually inspected for the actual airspeed, flap, gear, glideslope deviation, and altitude conditions that existed. Based on the actual conditions existing, it was determined whether a warning should have been generated, and if so, what type of warning should have been generated (see "Cubic GCAS" section). A comparison of what should have occurred with what actually happened was then made. This allowed the experimenters to determine the success rate of the algorithm in accurately providing a warning for the approach and landing phase of flight.

Out of 309 possible data points, 298 correct identifications were made. A correct identification was made when no warning was provided and the actual conditions at the time dictated that no warning be provided or a warning was provided when a warning should have been provided. This represented a success rate of 96.4%.



CATEGORY	A	B	C	D
S-ILS 24R	320/18 200 (200-½)			320/20 200 (200-½)
S-LOC 24R	620/24 500 (500-½)		620/40 500 (500-¾)	620/50 500 (500-1)
SIDESTEP RWY 24L *	620/50 500 (500-1)			620-1½ 500 (500-1½)
ARBIE DME MINIMUMS				
S-LOC 24R †	460/24 340 (400-½)			460/40 340 (400-¾)

Knots	60	90	120	150	180
Min:Sec	6:12	4:08	3:06	2:29	2:04

Figure 74. Example of ILS approach plate to RWY 24R Los Angeles.

The failure of the algorithm to identify 11 data points was broken into two categories. The first category was called "false alarms." This category represents the times when the algorithm provided a warning and no warning should have been given.This occurred seven times for a false alarm rate of 2.3%. The other category, "misses," represents the occasions when the algorithm failed to generate a warning when a warning should have been applied. This occurred 4 of 309 times for a miss rate of 1.3%. The total failure rate of the approach and landing sub-algorithm was 3.6%.

A breakdown of the misses and false alarms revealed all the misses were a result of the algorithm's inability to accurately provide warnings for glideslope deviation. Three glideslope warnings were inhibited due to other warnings. No priority of warnings existed in the Cubic GCAS algorithm. Consequently, the algorithm simply prioritized the warnings through alphabetization. Only one miss occurred from the algorithm's failure to provide a glideslope warning for a glideslope deviation to the low side. Of the seven false alarms, two were the result of a glideslope warning being given below a 250-foot altitude. As explained earlier, the minimum altitude for which a glideslope warning is to be given by the Cubic GCAS algorithm is 250 feet (AGL). The remaining five false alarms resulted from a "pull-up" warning being generated whenever the pilot bounced the aircraft on landing and then attempted to force the aircraft back down for the final full stop. Although the conditions would dictate a "pull-up" be generated, a warning at such a critical time was considered to be a nuisance, since impact (touchdown) with the ground is the intent of the landing. The incorporation of an inhibit would be appropriate.

Part 2 Discussion

Phase III evaluated the Cubic algorithm's ability to accurately provide safe minimum clearances to a real pilot in a consistent manner. By including the human pilot into the evaluation, we were able to evaluate the current algorithm with the human factor concern considered in the design. This allowed the formulation of the pilot window of acceptability. This window should be useful to the algorithm's designers, given it graphically describes the trend of the data, making areas needing additional development more obvious. It also provides the SPO engineers with a preliminary tool for evaluating the false alarm criteria set forth in the statement of work. The window of acceptability should be developed further by increasing the number of pilots participating in the evaluation. This would provide a window of acceptability more representative of the pilot crew force and of the warnings' relationships with minimum recovery altitudes and vertical velocity.

Our evaluation determined the Cubic algorithm provides inconsistent minimum clearances resulting in a high degree of variability. Further analysis revealed the algorithm failed to adequately account for the effects of slope during high terrain slope conditions. An analysis of the GCASLAND and TCHDWN subroutines revealed these subroutines had a prediction accuracy rate of 96.4%. However, the pilots suggested a glideslope warning for a deviation to the high side of glideslope would also prove very beneficial and should be recommended. An inhibit of the "pull-up" message during a bounce on landing should also be incorporated. Additionally, some priority of message warning should be established within the Cubic algorithm.

PHASE IV

The objective of the fourth phase of the evaluation was to introduce the pilot to a full mission using an actual terrain database. By doing so, the pilot was able to fly the simulator under normal flight conditions over terrain and obtain real time radar altimeter information. This scenario allowed the GCAS algorithm to be evaluated under normal operational flight profiles, and also helped reduce possible pilot response biases that might have occurred in Phase III. Response bias would be reduced because Phase IV pilots would be uncertain of an upcoming GCAS warning; whereas, Phase III pilots were guaranteed to hear a warning on every dive configuration trial. The procedure and results of Phase IV follow.

Method

Subjects

Eight of the nine pilots from Phase III of our evaluation were again used during Phase IV. The one pilot not involved in Phase IV was used as a checkout pilot for the full mission scenario.

Apparatus

Facility. Refer to the Phase II Apparatus section for a description.

Computer Complex. Refer to the Phase II Apparatus section for a description.

Simulator. Refer to the Phase II and Phase III Apparatus sections for a description of the KC-135 simulator. In addition, a computer program read a Defense Mapping Agency (DMA) terrain database into memory of a Gould Sel 87 computer. The elevation of the terrain was then computed based on an extrapolation of the simulator's position in relationship to the database. The subtraction of the terrain elevation from the aircraft's barometric altitude (computer based) provided the above ground information fed back to the aircraft's radar altimeter indicator.

Experimenter's Console. Refer to the Phase III Apparatus section for a description.

Voice Message Unit Mechanization. Refer to the Phase III Apparatus section for a description.

Audio Systems. Refer to the Phase III Apparatus section for a description.

Visual Warning Signal. Refer to the Phase III Apparatus section for a description.

Procedure

This portion of the evaluation was performed on the same day as Phase III. However, the pilots flew the Phase IV full mission during the afternoon after a minimum of a one hour lunch break. Upon return, the pilot was given a standardized briefing concerning the requirements of the mission. No additional simulator training was given the pilot since ample flight time had resulted from the Phase III portion of the evaluation. None of the pilots considered this a problem.

The mission required the pilot to takeoff on Runway 25R at Los Angeles and begin a climb to 12,000. At 2,000 feet, the pilot was required to turn right and fly direct to Santa Catalina tacan. From that point on, the pilot was briefed to fly the planned route and altitudes, unless told by the navigator, LA center, or the experimenter (all roles were played by the experimenter) to deviate from that planned (See Figure 75). Multiple interactions and interventions with the navigator and LA center occurred throughout the flight to simulate realistic flight communications. The interactions were both planned and random in nature. Pilots were informed an intervention by center or the navigator did not necessarily indicate a warning was forthcoming. On the contrary, less than twenty percent of all the ground impacts or warnings occurred outside the two minute period following an intervention.

The pilot was normally required to fly the aircraft at altitudes under 1000 feet (AGL) in an effort to place the aircraft in an environment where GCAS warnings would occur. Although this environment is not typical for a tanker, none of the pilots felt that it represented a major difficulty, since they were only required to fly the aircraft under normal flight profiles (i.e., straight and level, standard climbs and descents). The pilot was allowed full use of his instruments with the exception that the radio altimeter bug switch had to be set to less than one hundred feet, so the light would not allow the pilot to anticipate a possible GCAS warning. During flight, the experimenter could continually track aircraft position and configuration through the experimenter's console (Table 10).

<u>Table 10. An example of the mission data display page for Phase IV.</u>

FLY DATA DISPLAY PAGE

GAMMA	.0	PITCH	.0	ALT	135
ROLL	.0	AOA	.0	RALT	9
IAS	3	GS	1.00	VVI	-2
				WARN:	(NO WARNING)

KC135 STATUS		LANDING CONDITIONS		DATA COLLECTION	
(FLYING)		GEAR	0%	RUN :	1
		FLAPS	5%	DATA :	(INACTIVE)
TCN CH	83.0X	GS DEV	-3.0		
BRG	48.0	LOC DEV	.0		
		DME	.0		

Press ATTENTION to EXIT DATA

In the event of a crash, the pilot would continue to fly the simulator as though the impact with the ground had not occurred. The pilot and experimenter were made aware of a crash by the zeroing of the radio altimeter with a simultaneous clicking sound as the aircraft impacted the terrain. Under extremely hard impacts or well below ground impacts, the simulator was required to be reset. The experimenter would reset the simulator at the point of impact, but at an altitude high enough to avoid an immediate crash with the ground. The pilot was then briefed on the aircraft position and configuration and asked to state when he was ready for release. When the pilot was ready, the simulation would continue and the pilot would again fly the simulator as briefed. The planned mission was

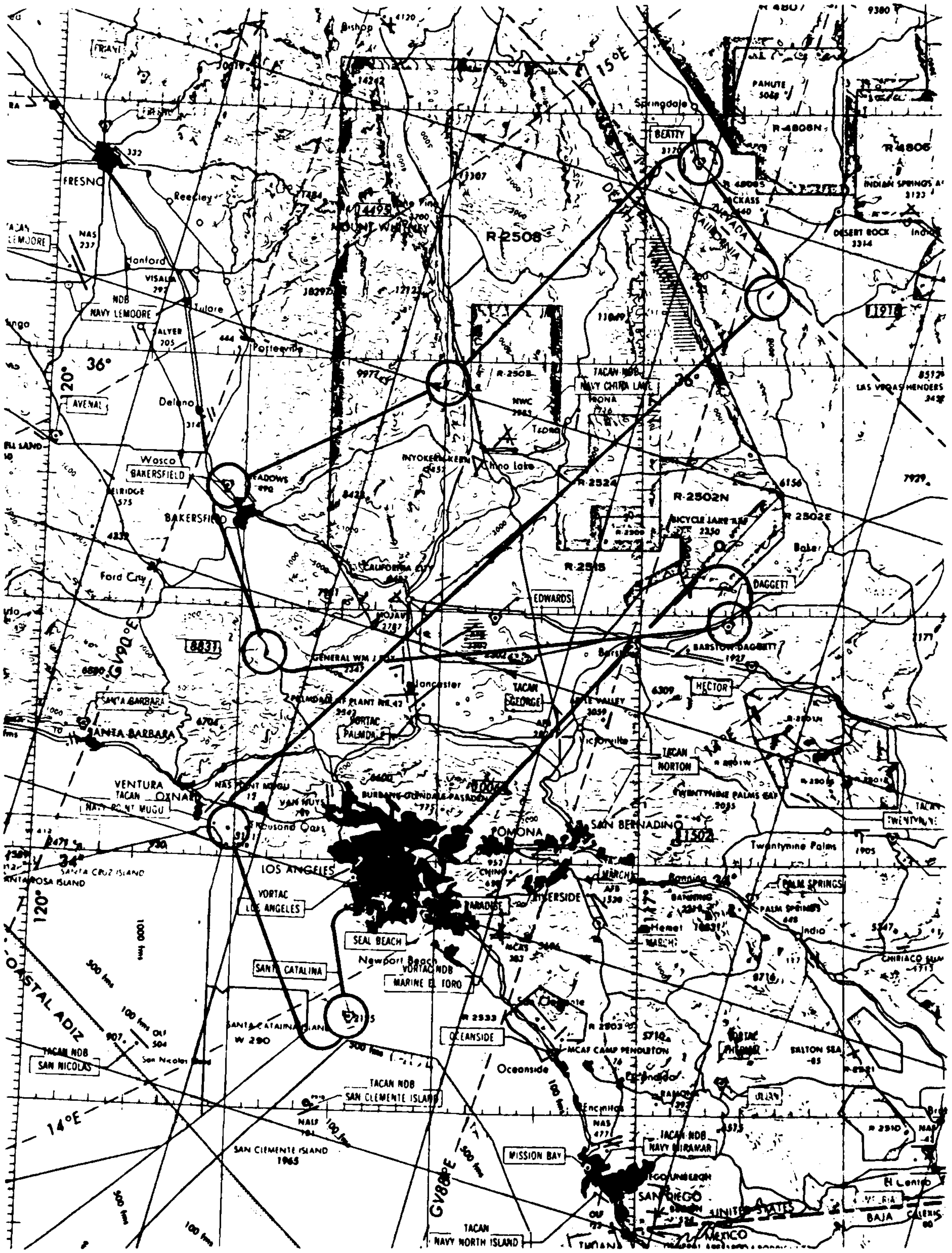


Figure 75. Example of the Phase IV full mission routing.

scheduled for two and one half hours. Due to numerous crashes for each pilot, no pilot successfully completed the entire mission. When the simulation portion of Phase IV was terminated, the pilot was given two questionnaires to gather their subjective opinions concerning the implementation of the GCAS, the reliability of this GCAS algorithm, and the quality of the simulation provided. These questionnaires can be found in Appendix B. The pilot was then debriefed and thanked for his/her participation in Phases III and IV of our evaluation.

Data Collection

Data were collected on a 15 Hz cycle for the duration of the mission. Two categories of variables were recorded: Algorithm calculations and actual parameters. These are explained in more detail in the results section. In order to make the data set manageable and to adequately evaluate the algorithm's predictive ability, only data points where an actual GCAS warning was given or when a crash occurred were placed into the database for final analysis. This resulted in a database of 82 data points. The data collection window for a given data point was the period 30 seconds before the event to sixty seconds after the event. Minimum clearances and maximum g's were based on the window.

Results

The data were sorted by minimum clearances, gamma, and terrain slope. A frequency analysis revealed the 82 data points consisted of 78 warnings, 2 crashes with no warning, and 2 false alarm warnings. A review of Table 11 reveals that 39 of the 78 warnings resulted in ground impacts. With the two crashes that received no warning, the final total is 41 of 82 (50%) possible data points resulted in aircraft crashes.

Table 11. Phase IV- Full mission data point frequency breakdown.

82 - Total data points

- 2 - Crashes with no warning generated
- 2 - False Alarms
- 78 - Warning generated
    - 20 - Valid warnings
    - 39 - Crashes
    - 10 - Below 50 feet (AGL)
    - 9 - 50 < Minclr <100

The data were further analyzed by breaking down the crashes by gamma. An analysis of Table 12 shows the majority of the crashes were for shallow dive angles or for climbing flight path angles. Our previous phases of the evaluation had focused on dive angles equal to or less than -5° nose down. Table 12 indicates the Cubic algorithm is having difficulty providing safe minimum clearances for flight path angles between -5° nose down to 10° nose up. For example, only one crash occurred for flight path angles

less than -5° (dives), but 13 crashes occurred for flight path angles between -1° and 0° (shallow dive-near straight and level flight). A review of the flight path angles (climbs) greater than 5° (Table 12: 5<γ Breakdown) further indicates the crashes were the result of the terrain slope climbing faster than the aircraft. The algorithm was unable to adequately account for this condition.

Table 12. Phase IV - Full mission crash frequency breakdown.

39 Crashes

1 - Gamma (γ) < -5	$8 - \gamma < 1$
$5 - \gamma < -2$	$0 - \gamma < 5$
$7 - \gamma < -1$	$4 - \gamma < 10$
$13 - \gamma < 0$	$1 - 10 < \gamma$

5 < γ Breakdown

$\gamma = +5.16$	Slope = 11.71
$\gamma = +6.50$	Slope = 9.95
$\gamma = +6.62$	Slope = 12.51
$\gamma = +8.36$	Slope = +9.95
$\gamma = +11.09$	Slope = 15.89

The aircraft 's actual flight path in relationship to the terrain database was also plotted for each of the data points. Figures 76-80 are some examples. They display the subject number at the top of the page. The first five lines along the side of the graph were the algorithm's predicted altitude loss for each of the subroutines, GCASALRT, GCASROLL, and GCASDIVE, in addition to the algorithm's calculated safety buffer. These are then summed to obtain the total predicted altitude loss, ALT LOSS. The first reaction time listed was that used by the algorithm. The roll, gamma, altitude, airspeed, and vertical velocity (VZ), found in the second group of variables, were the actual conditions of the aircraft simulator at warning initiation. Maximum G's (MAX Gs) and actual total altitude loss (ALT LOSS) were the maximum values obtained during aircraft recovery. Minimum clearance (MIN ALT) represents the minimum distance between the aircraft and the terrain that occurred during the aircraft's recovery. The roll line and G's line, at the upper portion of the graph, represent the realtime roll and g-load values of the aircraft during its flight. The x-axis is the total running time since the mission began. The y-axis is the altitude of the aircraft in feet (MSL). The flight of the aircraft is represented by the curved upper line beginning at the higher region of the y-axis. The ground level is represented by the jagged line that begins at the lower region of the y-axis.

Figure 76 provides an excellent example of a false alarm. The simulator is flying in essentially a straight and level configuration, while the terrain is rapidly increasing. The warning is received at the moment the terrain levels off. The result was a false alarm. Figure 77 provides an example of the aircraft flying essentially a straight and level flight profile with rising terrain. The warning was provided early enough to allow for a minimum clearance altitude of 267 feet. This figure also provides an excellent representation of one of several mountain ridges the pilots were required to fly over during the mission.

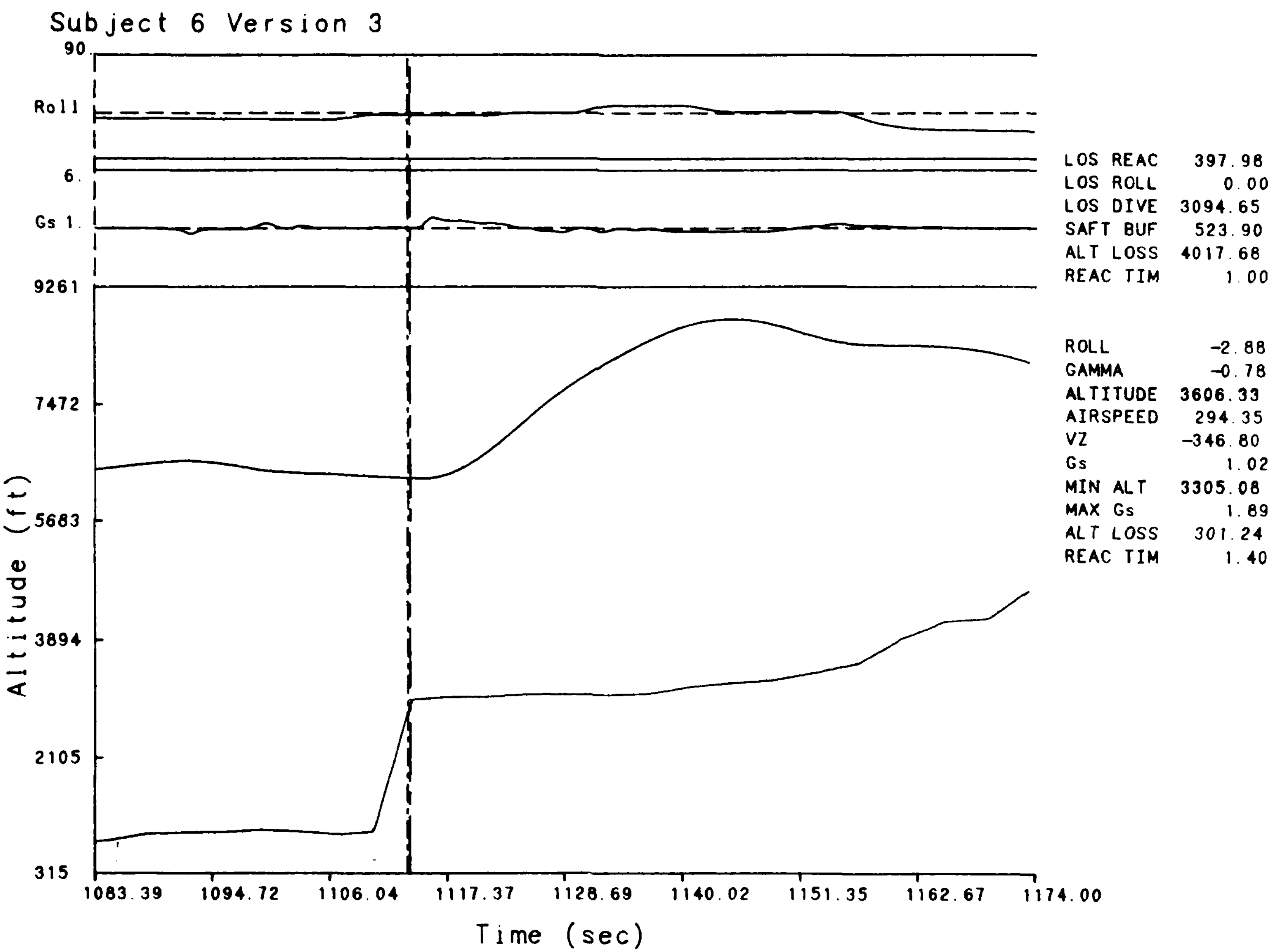


Figure 76. Example of a "false alarm" data point.

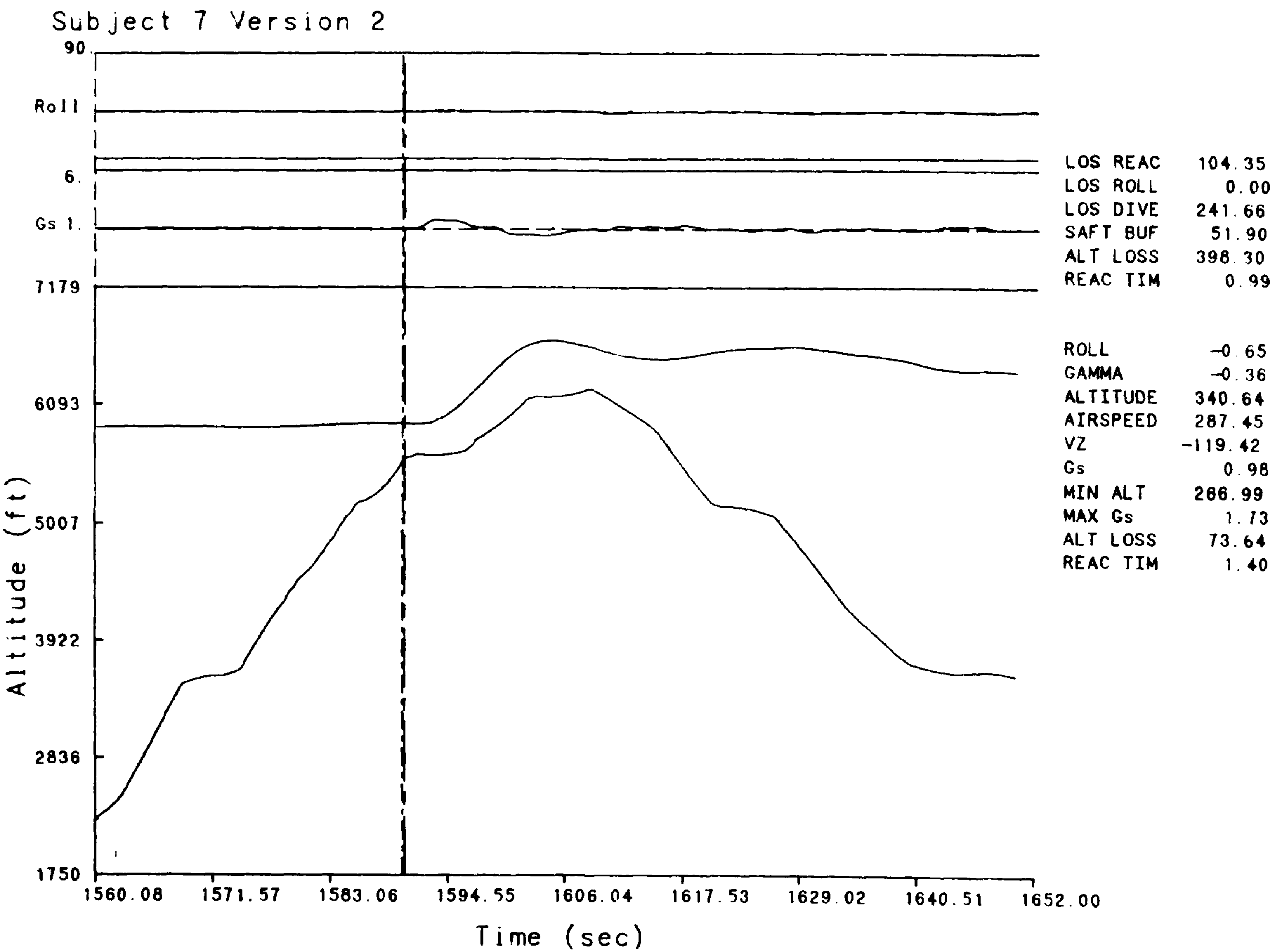


Figure 77. Example of a "straight and level flight with rising terrain" data point.

Figure 78 provides an example of a shallow descent profile into gently rising terrain. No warning was provided. The recovery was initiated because the pilot noticed the drop in altitude on the radio altimeter and responded accordingly. Figure 79 shows the algorithm's failure to provide the pilot with a warning early enough to affect recovery. Figure 80 is an example where the pilot began a climb as directed by the navigator. At the start of the climb, no warning had been sounded. A warning was finally generated during the climb, but it was just moments before impact. This provides another example of the algorithm's inability to account for flight path angles of shallow descent or climb.

Given the algorithm's inability to account for flight path angles greater than -5°, one final analysis was run in an attempt to isolate a possible source of the problem. In a similar fashion to the robot runs of Phase II, several GCAS warning trials were performed using the robot model. Unlike Phase II, the roll, gamma, and terrain elevation variables were kept constant at values of 0°, 2°, and 1000 feet, respectively. The independent variables were airspeed (225, 275, & 325 knots) and slope (3.5, 7, 10.5, & 14 degrees) with the dependent variables of interest being minimum clearance altitude and warning initiation altitude.

Figures 81 and 82 provide us with pictorial representations of the results. If the algorithm was performing calculations based on terrain slope, the warning altitudes should have increased as the slope of the terrain increased. A glance at Figure 81 shows just that. The warning altitude did increase as the slope of the terrain increased, across all airspeeds. Since the algorithm is considering slope effects, then it may be the algorithm failed to calculate the effects of slope accurately. Figure 82 indicates this is the underlying problem. If the algorithm were accounting for the effect of slope accurately, we would expect minimum clearance to increase as slope increased (explained earlier in Phase II). This is not what Figure 82 indicates. Rather than an increase in the minimum clearances, there was a decrease in the minimum clearances. Additionally, all of the minimum clearances for slopes greater than 3.5° resulted in crashes (Figure 82).

Discussion

The results of Phase IV demonstrated the algorithm's inability to accurately account for the effects of slope. This inability was due to the algorithm not providing adequate increases in warning altitude as a result of slope effects. This problem was further aggravated under flight path angle conditions greater than -5°. Additional effort must be directed at correcting this deficiency. Additionally, two false alarms occurred which resulted in minimum clearances greater than 1800 feet. Further refinement of the algorithm should consider the possibility that an over correction for the effects of slope may cause an increase in false alarms. This would also be an undesirable situation as pilot confidence in the algorithm would be greatly undermined. Future efforts should consider the possibility of such a trade-off.

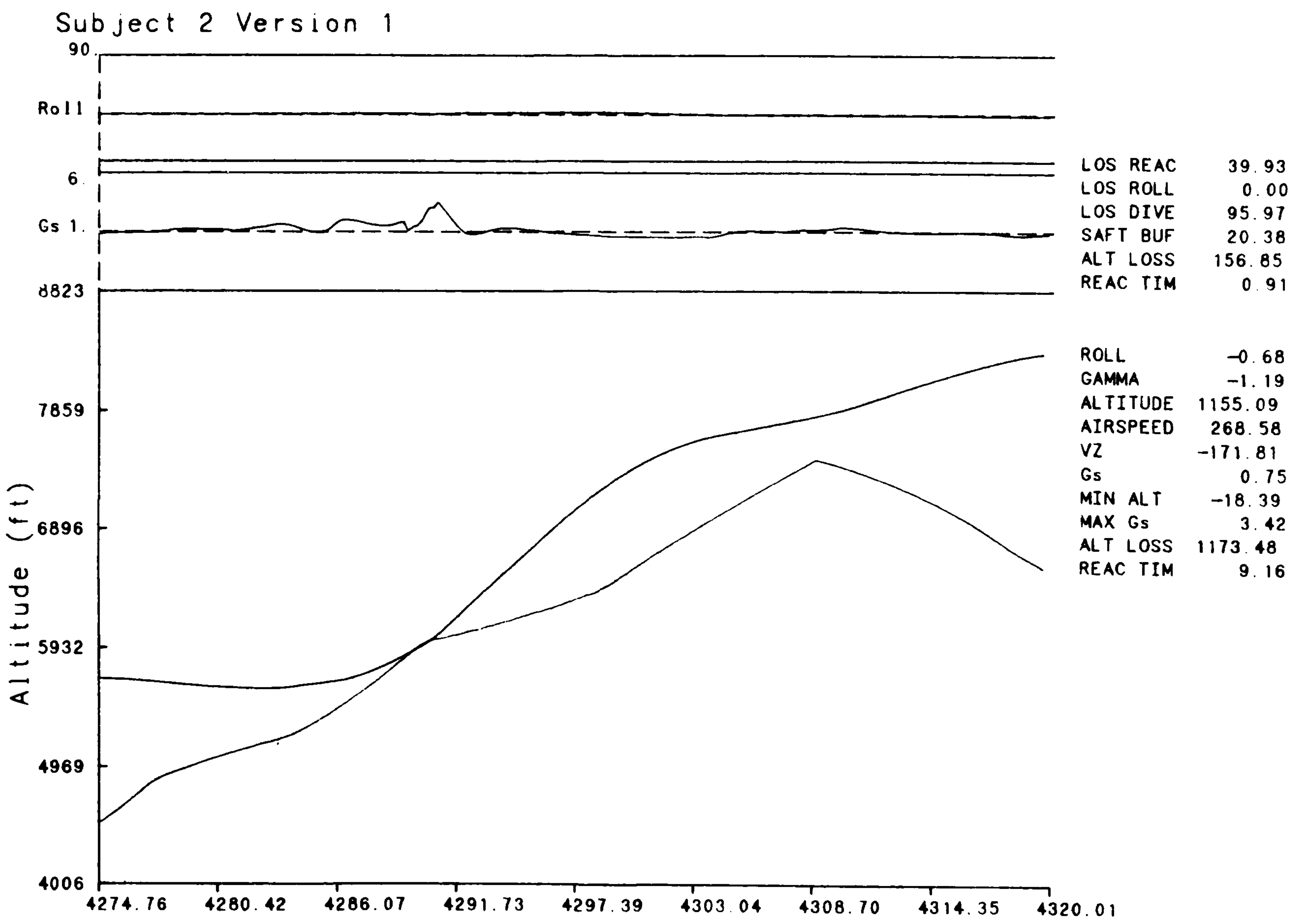


Figure 78. Example of a "shallow descent into gently rising terrain-late warning" data point.

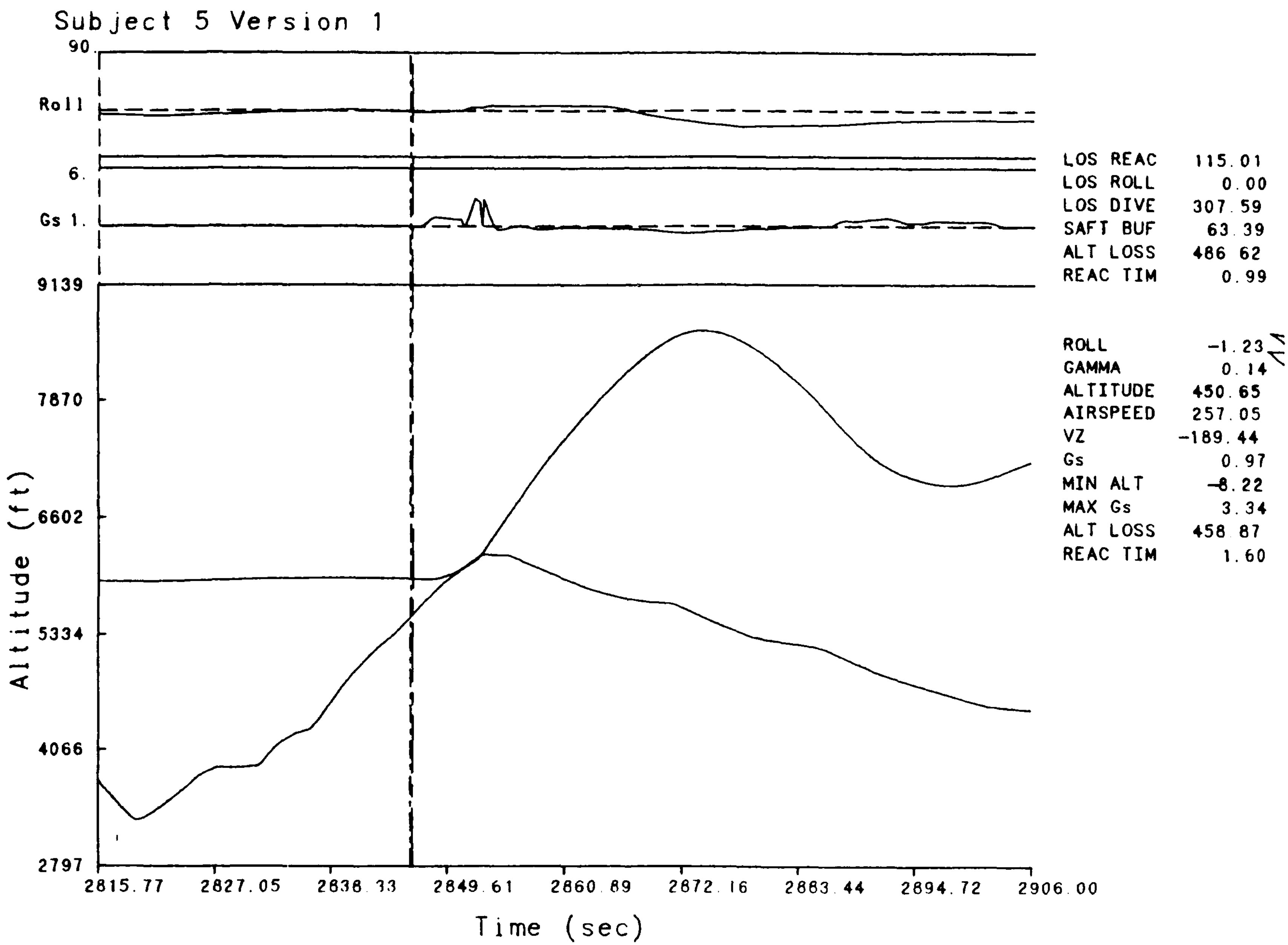


Figure 79. Example of a "straight and level flight-late warning" data point.

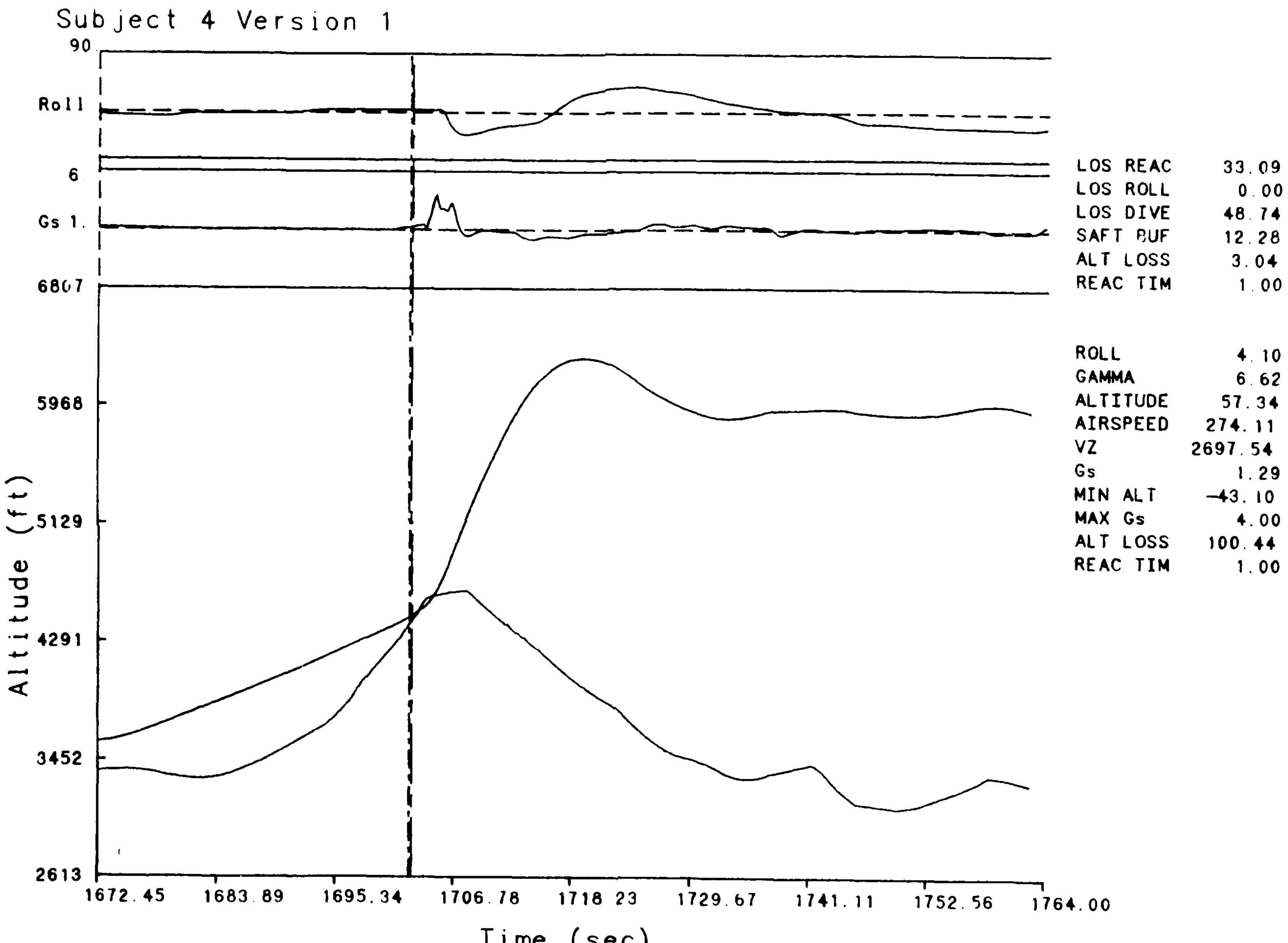


Figure 80. Example of a "climb with rising terrain-late warning" data point.

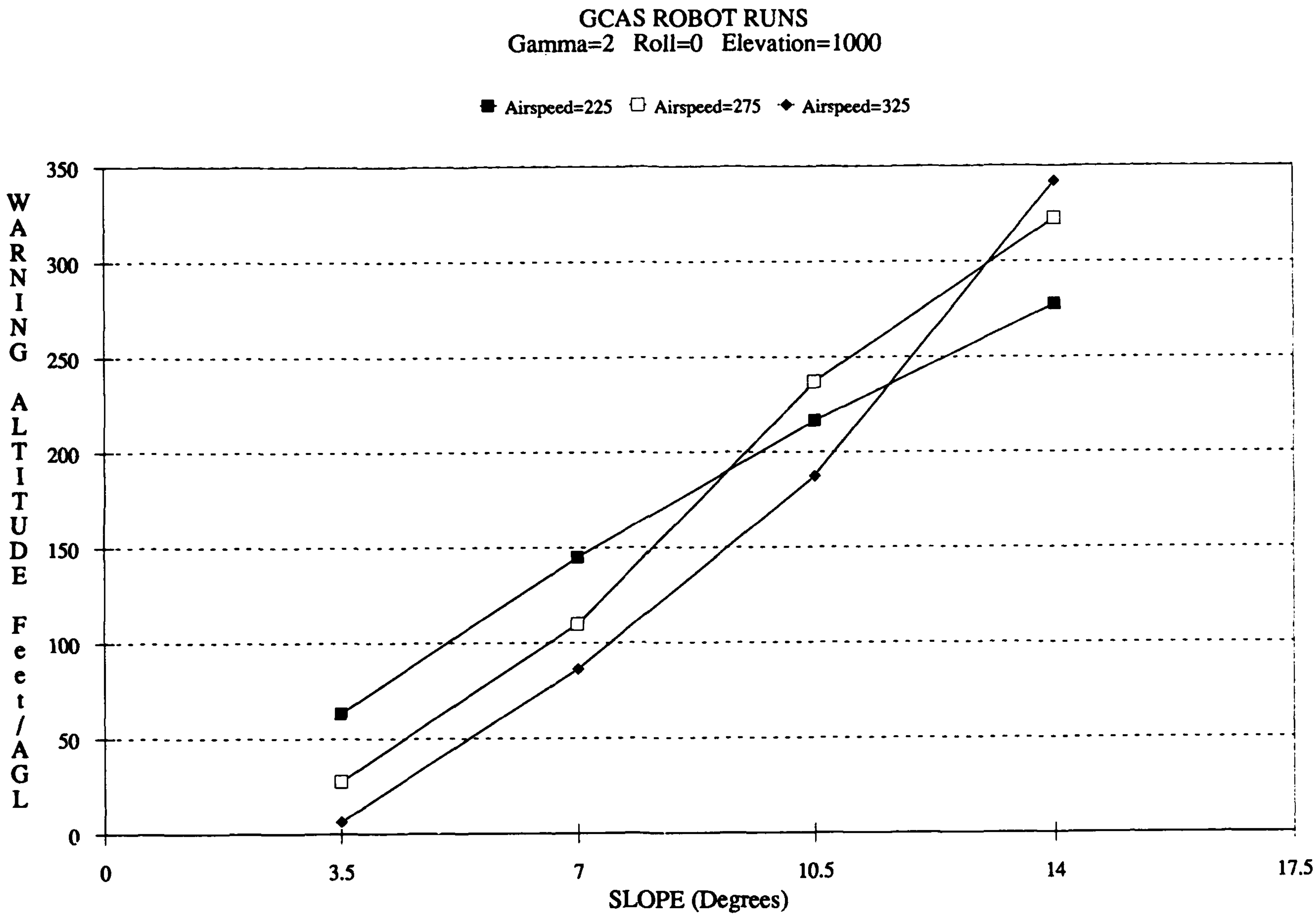


Figure 81. Warning altitude as a function of slope for pilot model: Gamma=2, Roll=0, & Elevation =1000.

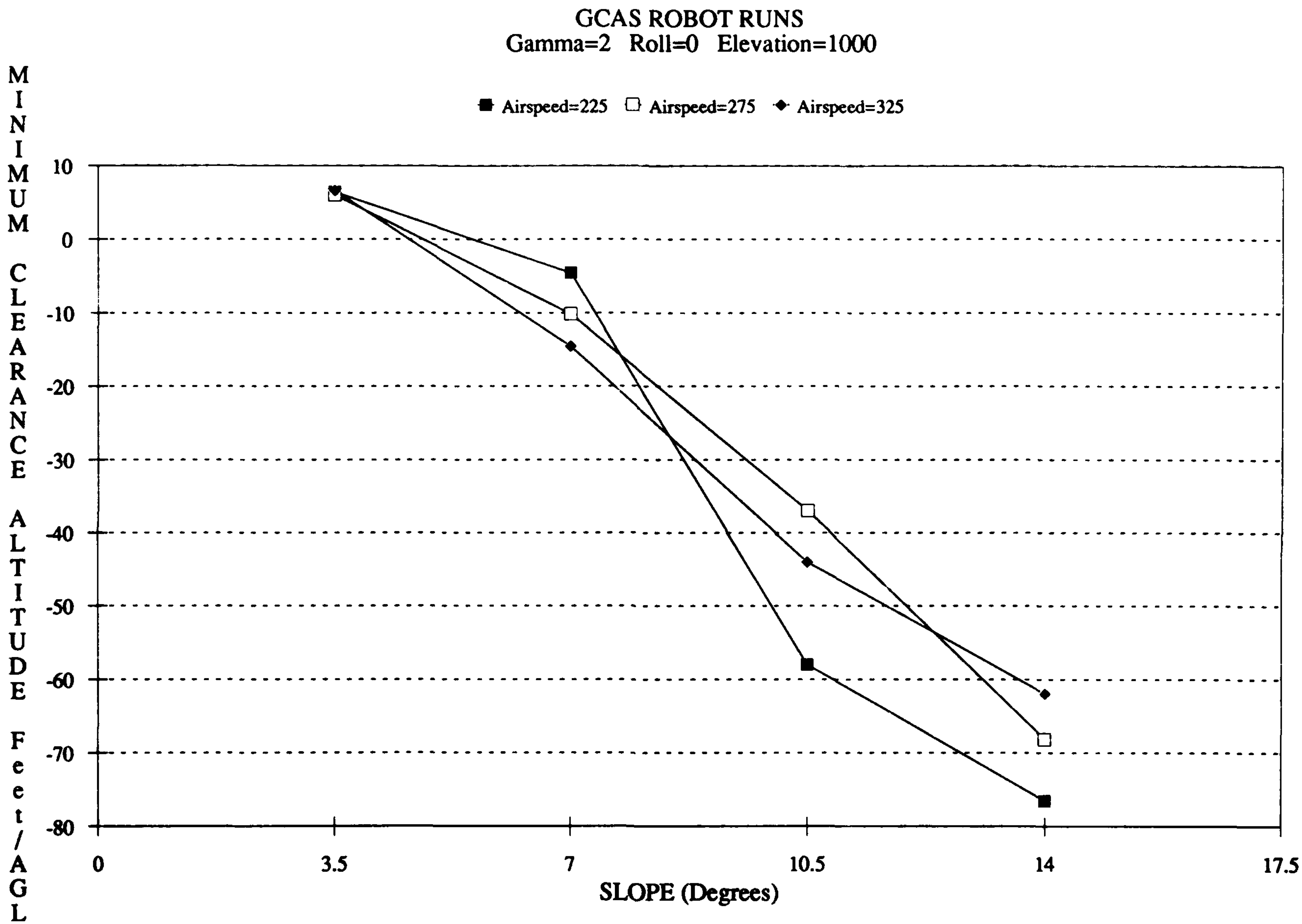


Figure 82. Minimum clearance as a function of slope for pilot model: Gamma=2, Roll=0, & Elevation=1000.

PILOT QUESTIONNAIRES

At the completion of Phase IV, the subjects were required to answer the two questionnaires found in Appendixes B & C. The questionnaire titled "Ground Collision Avoidance System Questionnaire For Cargo/Tanker Type Aircraft" (Appendix B) was originally mailed out to operational KC-135 bases to gather aircrew subjective data concerning the possible implementation of a GCAS system into the KC-135 aircraft. Some of the results of this questionnaire (Rueb & Hassoun, 1990) provided valuable information for designing the simulator warning signals used for this study within current military requirements (Mil Std 1800, Mil Std 411D). The second questionnaire was used to evaluate the algorithm and the CSEF simulator.

The "KC-135 Ground Collision Avoidance Questionnaire" results for this study (N=9, hereafter referred to as Study B) paralleled that of the original study (N=82, hereafter, referred to as Study A) with the following exceptions. First, the pilots (8 of 9) in Study B definitely felt a voice warning was the preferred aural mode of warning. There was a fairly even split between voice and tone preference for Study A. Study B respondents also felt the GCAS should not be able to be shutoff. Instead, they felt a reset capability would be advantageous. Additionally, the Study B pilots felt the maximum altitude coverage of the GCAS should be limited to the maximum coverage of the radar altimeter; whereas , Study A indicated a maximum coverage of 5000 feet would be appropriate. Given the pilots in Study B had actual experience with a GCAS, we placed more credence in the idea that the maximum altitude of the GCAS be tied directly to that of the radio altimeter.

Another difference between the Study A population and Study B's subject population is the response given to the nomenclature that should be printed on the warning light. Study A respondents preferred "Altitude;" Study B pilots preferred "Pull-up." Since they preferred the voice warning, "Pull-up," used in the study, they felt the light nomenclature should also reflect "Pull-up." This finding supports the findings of Hassoun, Kinzig, & Barnaba, (1988).

With the exceptions noted above, the Study B responses validated the subjective responses provided in Study A. Recall Study B subjects had actually flown a GCAS-equipped simulator. Study A respondents had not had any experience with a GCAS system. This is important because it substantiates the utility of questionnaire data.

The results of the untitled second questionnaire (Appendix C) supported the findings of this evaluation. Specifically, the pilots felt the overall ground clearance of the Cubic GCAS algorithm was slightly low (5 of 9). They also felt the Cubic algorithm applied its warnings inconsistently (7 of 9), and consequently, were not confident (6 of 9) in the algorithm. This is a direct result of the high variability identified during Phases III and IV of our evaluation. The subjects did, however, believe the use of the Cubic GCAS algorithm would still be beneficial for the KC-135 aircraft. This was based primarily on their ideas that any system that prevented even one accident is beneficial.

The whole premise underlying this study is based on this simulator's fidelity and realism. The degree that the performance of the simulator mirrors that of the aircraft represents the degree of confidence that we can place in our findings. Two subjects found the simulator performance to be excellent, five found it to be good. Only one felt the simulator was fair in performance, but did not state why. Based on the results to this question, we can place a high degree of confidence in this study's findings.

CONCLUSIONS AND RECOMMENDATIONS

Since the problems of Phase I and Phase II were corrected prior to the next phase of the evaluation, this section will focus only on our findings and recommendations for Phases III and IV. After an extensive and in-depth analysis, several problem areas were identified. Specifically, the Cubic GCAS algorithm:

a. Provided too much variability in the minimum clearance altitudes under high terrain slope conditions.

b. Failed to account for the effects of slope under low dive angles and under climb conditions.

c. Failed to provide for message priority.

d. Failed to provide a warning to the high side of glideslope.

e. Provided a nuisance "pull-up" warning for bounces that occurred during landing.

f. Failed to provide the pilot with enough time to recover the aircraft for landing on that approach, based on the current flap and gear warning being given at 500 feet AGL.

Based on our findings, we recommend the current version of the Cubic GCAS algorithm not be used. The following corrections to the Cubic algorithm should be made:

a. The possible inclusion of the effects of Cg into the algorithm should be considered.

b. The algorithm should be adjusted to better account for the effects of slope.

c. The algorithm should cover a flight path angle range of 20 degrees nose down to 15 degrees nose up.

d. The algorithm should provide a warning for glideslope deviations to the high side of glideslope.

e. The algorithm should provide a minimum ground clearance of 150 feet (AGL) and a maximum ground clearance of 1000 feet (AGL). A general rule of thumb is approximately 10% of the downward vertical velocity of the aircraft at warning initiation.

f. Measures should be included to inhibit the pull-up message for possible bounces on the runway during landing.

g. Finally, if the approach and landing algorithm is intended to provide the pilot adequate time to effectively land the aircraft, then the gear and flap warnings should begin at 1000 feet (AGL), instead of the 500 feet currently used by the algorithm.

SUMMARY

The Cubic GCAS algorithm was evaluated in a four phase simulation effort. Phase I attempted to verify and validate the sub-algorithms. In Phase II, a robot pilot model was used to test the algorithm in the KC-135 simulator. The robot pilot model performed various dive recovery maneuvers. A subset of which were used in Phase III. Phase III and Phase IV involved man-in-the-loop simulation. At the conclusion of Phases I, II, and IV, recommendations were made to the SPO and the Cubic Corporation regarding possible refinements of the algorithm.

Hassoun, Ward, Barnaba, & McCarthy (1989) posed the question in reference to the pilot window of acceptability, "Can we generalize from the present study results, or should a new set of data be collected on each individual aircraft ?" (p. 150) Based on the results of our study, initial indications suggest the pilot window of acceptability should be generated based on individual aircraft. A comparison of the FB-111 and the KC-135 windows of acceptability (Figures 83 & 84) reveals significant differences in minimum clearances for the different vertical velocities. As explained by Rueb & Hassoun (1990), the x-axes for the two aircraft reflect much of the differences between the windows. The F-111 x-axis is in hundreds of feet per <u>second</u> (tens of thousands of feet per minute); whereas, the KC-135 x-axis is in thousands of feet per <u>minute</u>.

Future efforts should be directed at identifying pilot windows of acceptability to be used in the development of a GCAS system. These windows would provide both the developer and the SPO with an accurate method for evaluating the false alarm and prediction accuracy rates for a given GCAS system. Additional GCAS evaluations should also include man-in-the loop simulations interfaced with actual terrain databases. As shown by this study, this provides a realistic and informative method for evaluating the GCAS algorithm.

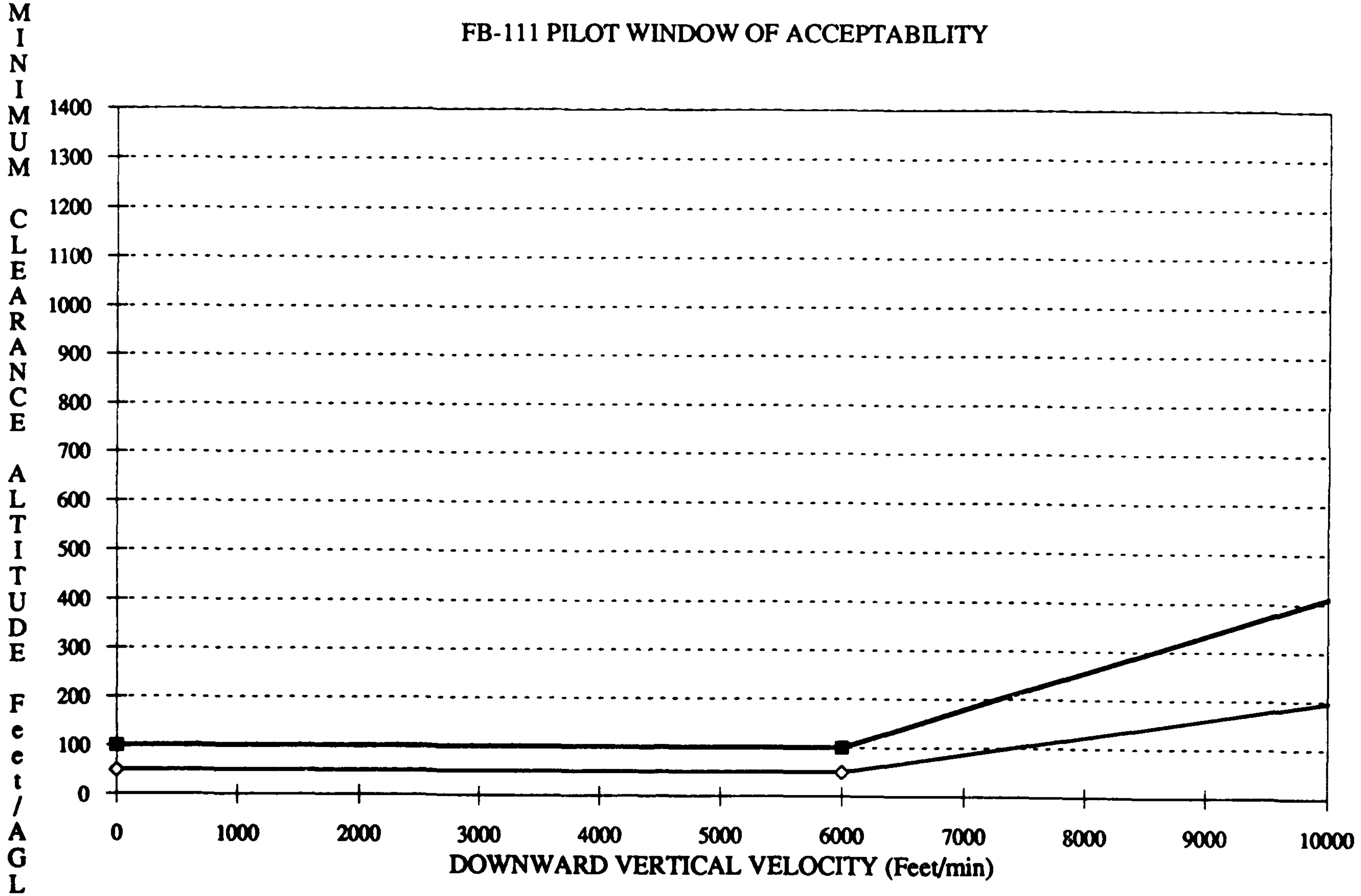


Figure 83. Pilot window of acceptability for FB-111 aircraft.

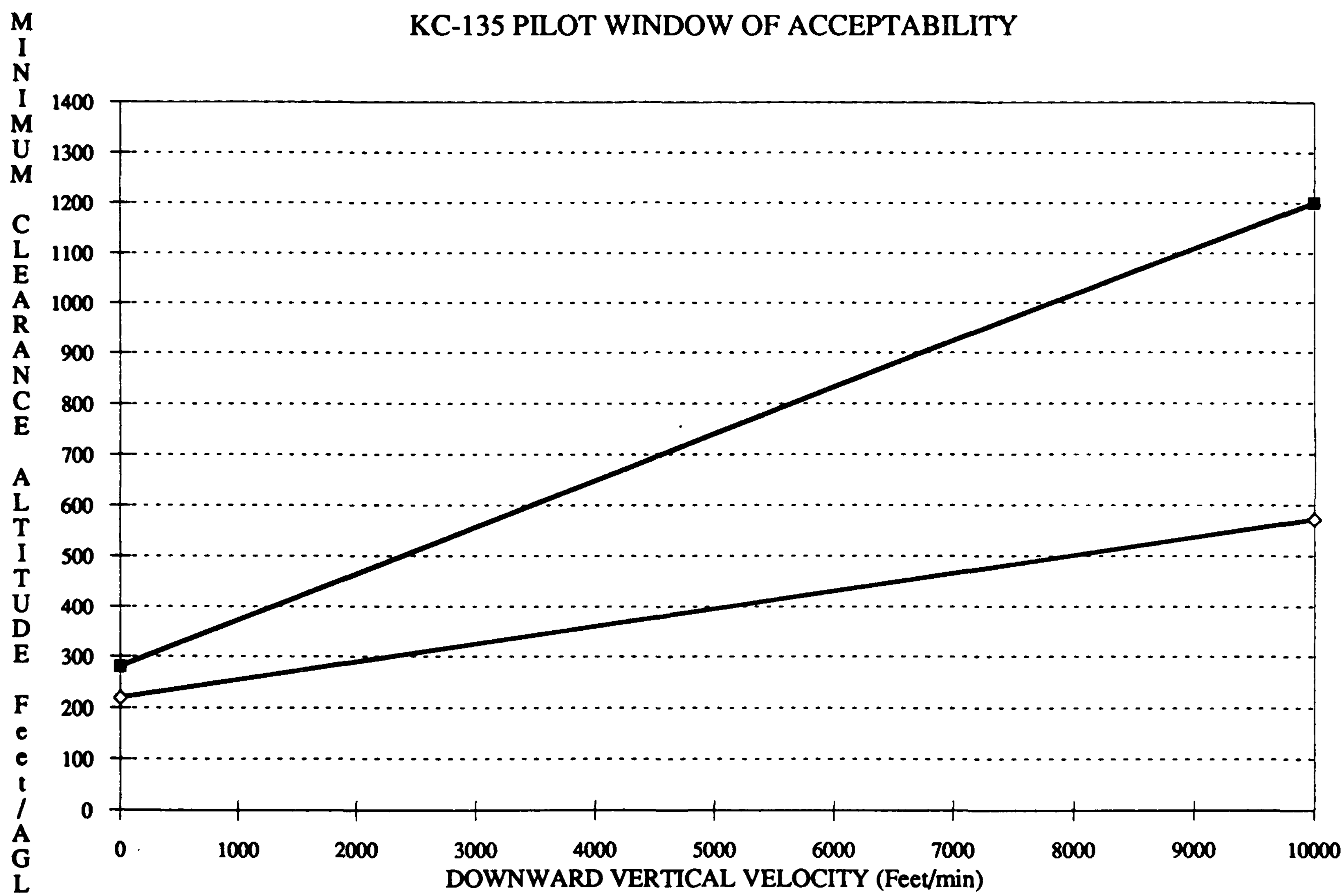


Figure 84. Pilot window of acceptability for KC-135 aircraft.

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APPENDIX A

CSEF-TR-89-135-01

CARGO/TRANSPORT/TANKER CONTROLLED FLIGHT INTO TERRAIN (CFIT) (1970-PRESENT) AND THE POSSIBLE IMPACT OF AN OPERABLE GROUND COLLISION AVOIDANCE SYSTEM (GCAS)

JUSTIN D. RUEB, CAPT, USAF
JAMES R. KINZIG

NOVEMBER 1989

CREW STATION DESIGN FACILITY
HUMAN FACTORS BRANCH
ASD/ENECH
WRIGHT-PATTERSON AFB, OHIO 45433-6503

1. INTRODUCTION

The following report describes cargo/transport/tanker Controlled Flight Into Terrain (CFIT) mishaps covering the period of 1970-Present. During this period, thirty-one CFIT mishaps occurred that involved cargo/transport/tanker type aircraft. The mishap aircraft included; 12 C-130's, 7 C-141's, 5 C/KC-135's, C-7, C-9, C-12, C-54, C-123, C-124, and C-140. Each mishap was classified into various categories (e.g., low level, mountainous terrain, night, etc.) to identify any trends. A brief statistical synopsis of these mishaps follows.

2. GCAS SYSTEM IMPACT

Figure A-1 presents a breakdown of the CFIT mishaps into three categories based on whether an operational Ground Collision Avoidance System (GCAS) could have prevented such an occurrence. The three categories are No Help, May Help, and Help. Two CSEF engineers determined these classifications based on the 1970-Present CFIT accident mishap reports. A No Help classification resulted when it was determined that an operable GCAS system would not have provided a warning signal (e.g., aircraft striking a tall tree, aircraft hitting the side of a sheer cliff/mesa). A May Help classification occurred when no exact determination could be made from the mishap report findings. An aircraft hitting the ground after acknowledging level at a given altitude or crossing a given tacan fix is an example of a May Help rating. A Help classification resulted when it appeared obvious that the mishap could have been prevented, given a usable GCAS onboard (e.g., aircraft crashes into the top of a mountain peak due to aircrew inattention). It was found that 13 accidents (42%) could not have been prevented by GCAS, whereas, 18 (8 May Help 26%, 10 Help 32%) mishaps, costing numerous lives and millions of dollars, may have been prevented by an operable GCAS system. Thus, there is ample justification for installation of a Ground Collision Avoidance System in the C/KC-135 fleet.

3. CLASS A MISHAP ANALYSIS AND RESULTS

Figure A-2 shows the breakdown of the mishaps according to the phase of flight and the effectiveness of the GCAS system. The rectangles with stripes canted right represent GCAS preventable mishaps. The left-canted striped rectangles represent those mishaps where GCAS would not have been effective. The approach and landing phase accounts for 50% of the mishaps; the low level phase, 33%. The takeoff and cruise phases together account for only 17% of the mishaps, half that of the low level phase. Accordingly, mission scenarios shall focus on the low level and the approach/landing phases of flight.

Figure A-3 categorizes the mishaps according to type of terrain where the aircraft mishap occurred. Of the preventable mishaps, mountainous terrain mishaps equalled flat and rolling mishaps. This finding may be biased toward the flat and rolling terrain. In determining type of terrain, it was assumed that all accidents not specifically mentioning a peak or mountainous type terrain occurred in flat and rolling terrain. This assumption fails to account for the possible oversight of the mishap investigator not reporting a mountainous condition when it might have existed. Accordingly, mission scenarios will include mountainous and, flat and rolling terrain.

Day and nighttime conditions are represented by Figure A-4. Daytime accounted for twice as many mishaps than nighttime conditions. This suggests the need to investigate daytime condition. However, further investigation reveals that the majority of flights (approximately 75%) occur during daytime conditions. Therefore, daytime conditions

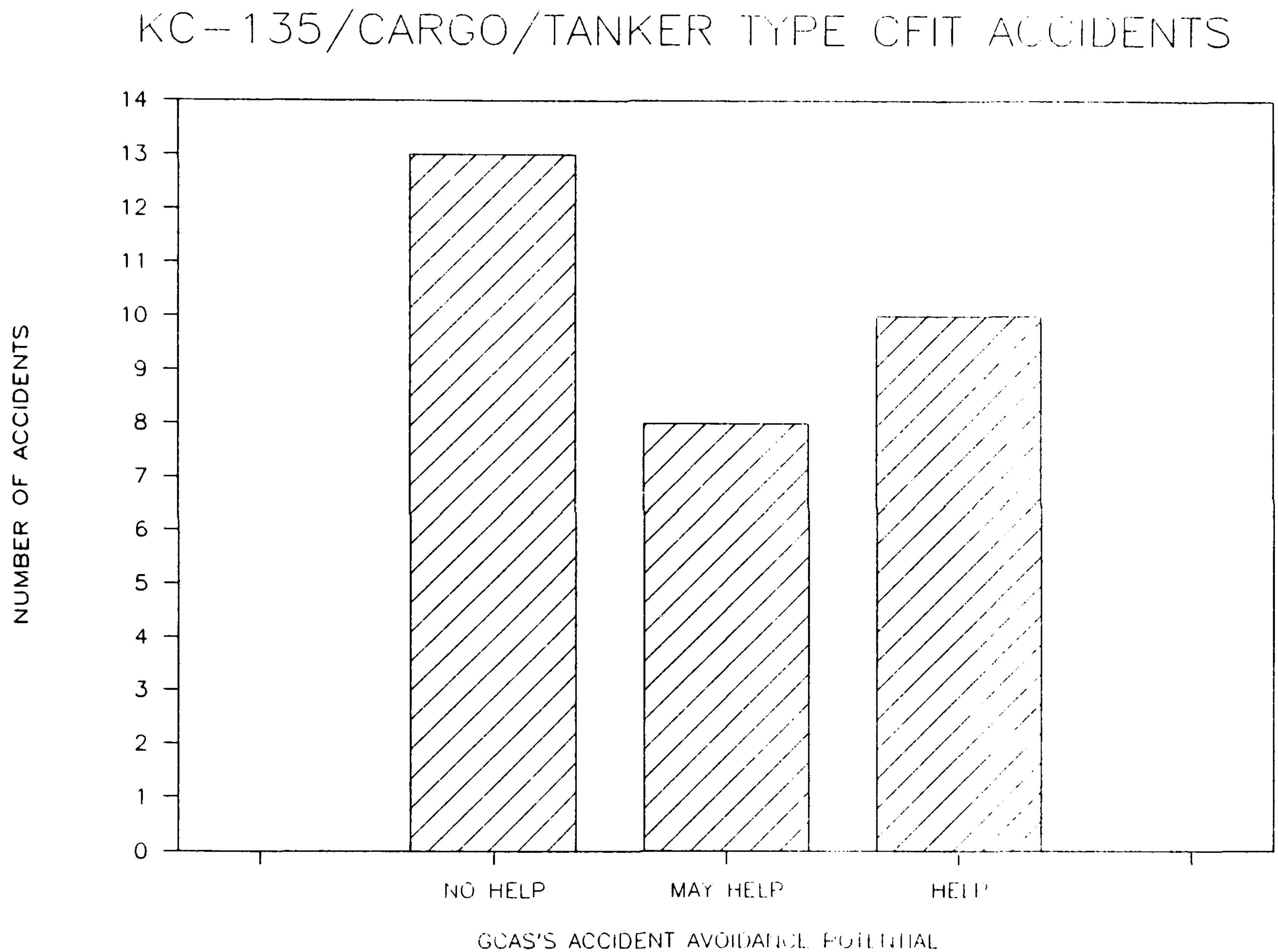
should be triple that of the nighttime conditions, but are only twice the number of nighttime mishaps. Accordingly, mission scenarios should focus on both daytime and nighttime conditions.

Daytime and night time conditions are further divided into categories based on whether adverse weather conditions existed (Figure A-5). This breakdown reveals that GCAS preventable mishaps were equally split between clear and adverse weather conditions for both the daytime and nighttime categories. In a similar fashion to day/night flights, this finding is slightly deceiving. A larger percentage of flights is conducted during clear sky conditions than during adverse weather conditions, because of ICAO/FAA flight safety restrictions.

Figure A-6, secondary causes, identifies those mishaps that involved other factors that may have contributed to the mishap. Two incidents involved malfunctioning aircraft, while six involved air traffic controller instructions (e.g., aircraft 29, cleared descent to 4000 feet). Of the six controller involved incidents, three (50%) involved instructions to maintain altitude or descend to altitudes that were below minimum safe clearance altitudes. A fourth mishap resulted from an aircrew incorrectly acknowledging a controller's clearance altitude. No malfunction related mishaps would have been avoidable.

4. CONCLUSION

Based on Figures A-1 through A-6, an operable Ground Collision Avoidance System would possibly have prevented 58% of the Controlled Flight Into Terrain mishaps. It also suggests that three GCAS modes might be beneficial: (1) Takeoff, (2) Low Level, and (3) Approach/Landing. Additionally, these figures indicate that mission scenarios should focus on the low level and approach/landing phases of flight, day and nighttime conditions, and both flat and rolling and mountainous type terrain. Thus, our evaluation shall focus on this type of mission scenario.



KC-135/CARGO/TANKER TYPE CFIT ACCIDENTS
NUMBER OF ACCIDENTS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
NO HELP
MAY HELP
HELP
GCAS'S ACCIDENT AVOIDANCE POTENTIAL

Figure A-1

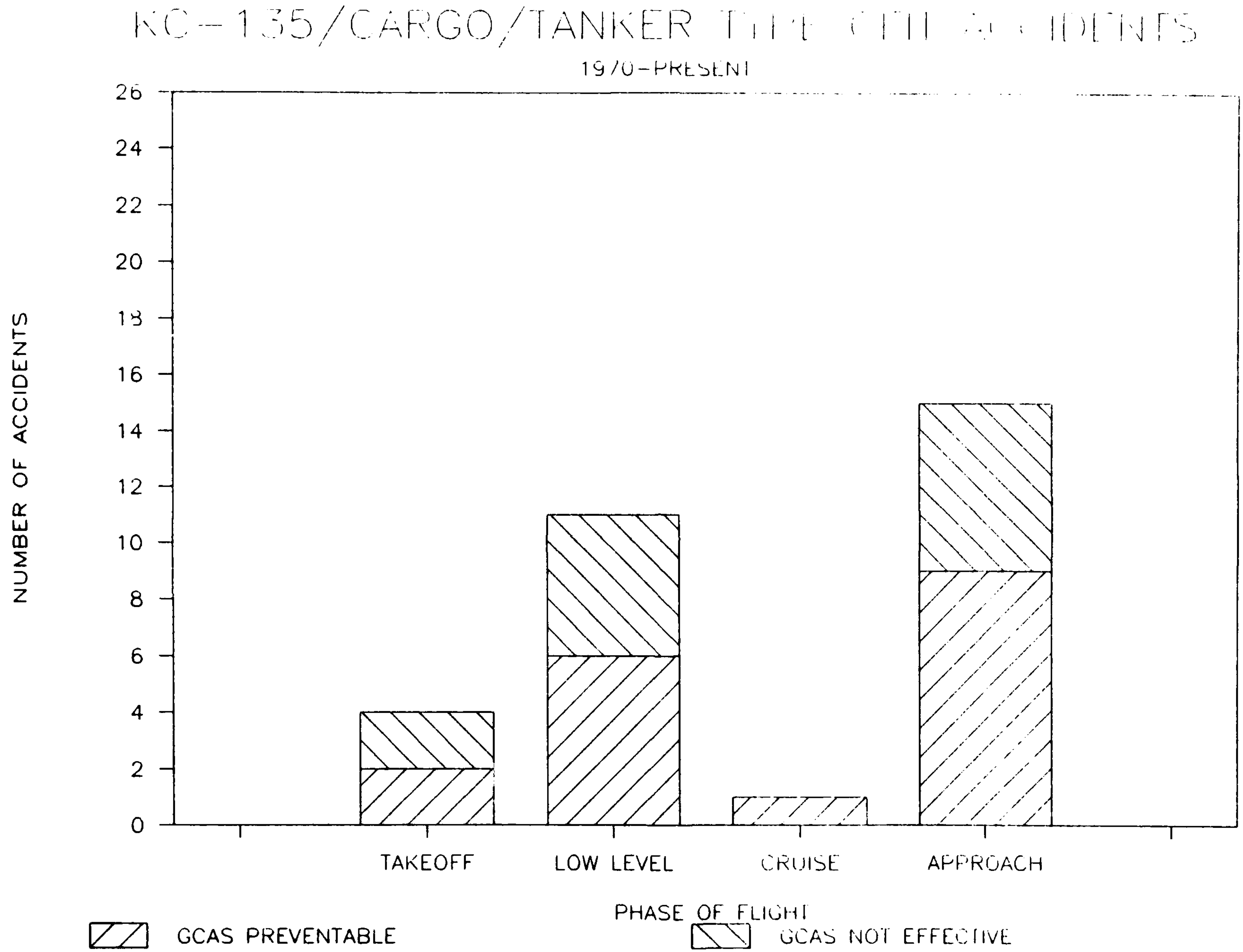

KC-135/CARGO/TANKER
1970-PRESENT
NUMBER OF ACCIDENTS
0
2
4
6
8
10
12
14
16
18
20
22
24
26
TAKEOFF
LOW LEVEL
CRUISE
APPROACH
PHASE OF FLIGHT
GCAS PREVENTABLE
GCAS NOT EFFECTIVE

Figure A-2

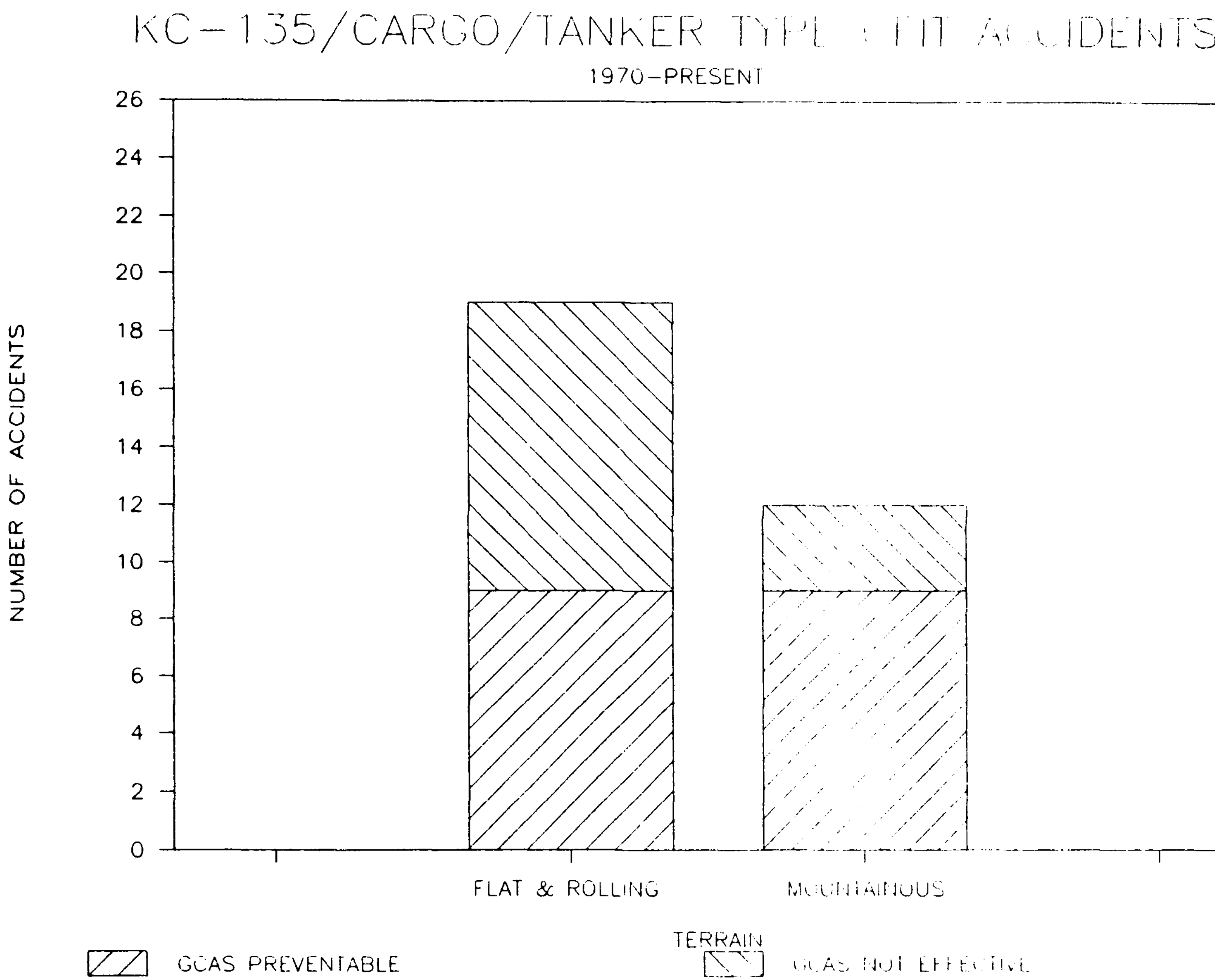

KC-135/CARGO/TANKER
1970-PRESENT
NUMBER OF ACCIDENTS
26
24
22
20
18
16
14
12
10
8
6
4
2
0
FLAT & ROLLING
TERRAIN
GCAS PREVENTABLE

Figure A-3

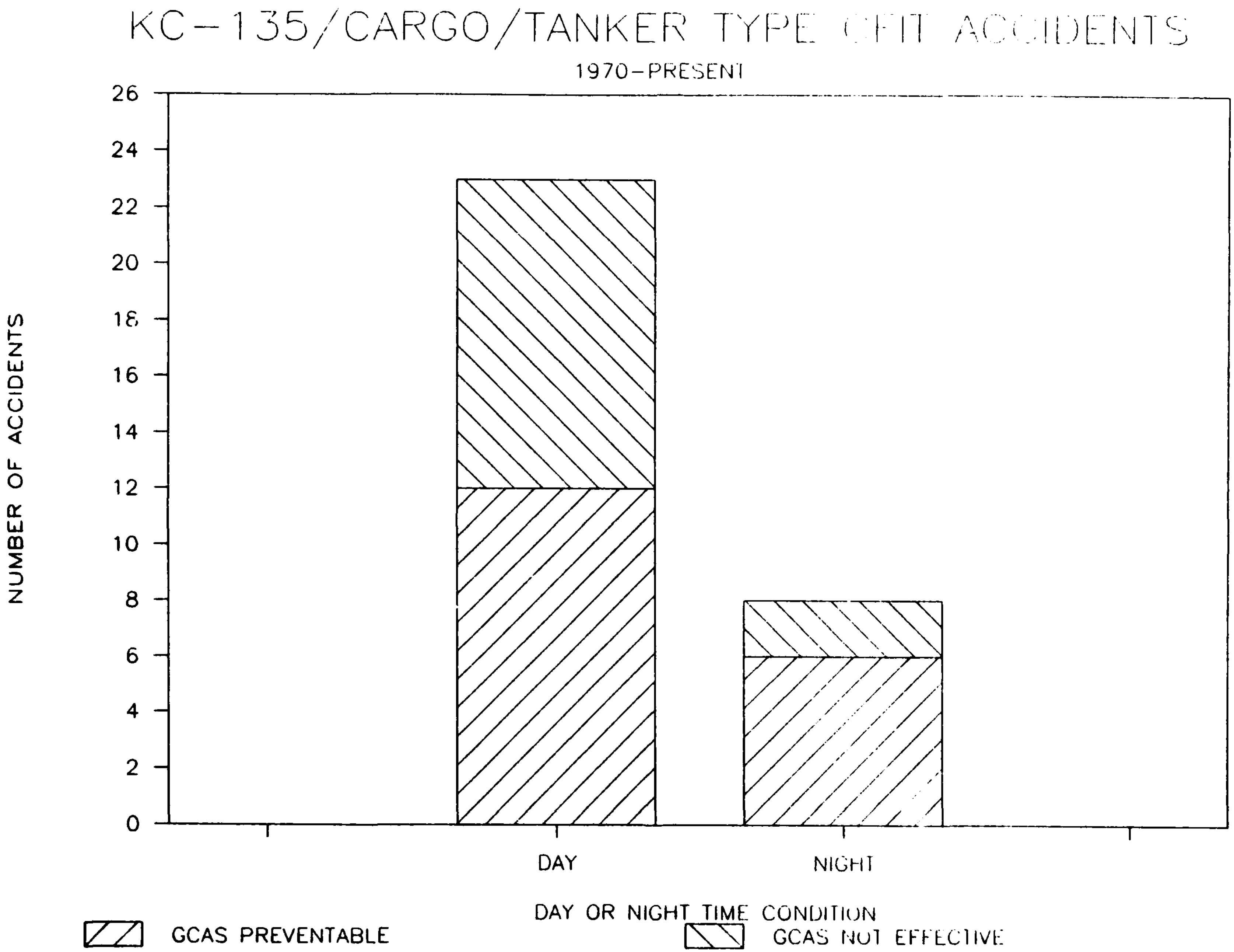

KC-135/CARGO/TANKER TYPE CFIT ACCIDENTS
1970-PRESENT
NUMBER OF ACCIDENTS
26
24
22
20
18
16
14
12
10
8
6
4
2
0
DAY
NIGHT
DAY OR NIGHT TIME CONDITION
GCAS PREVENTABLE
GCAS NOT EFFECTIVE

Figure A-4

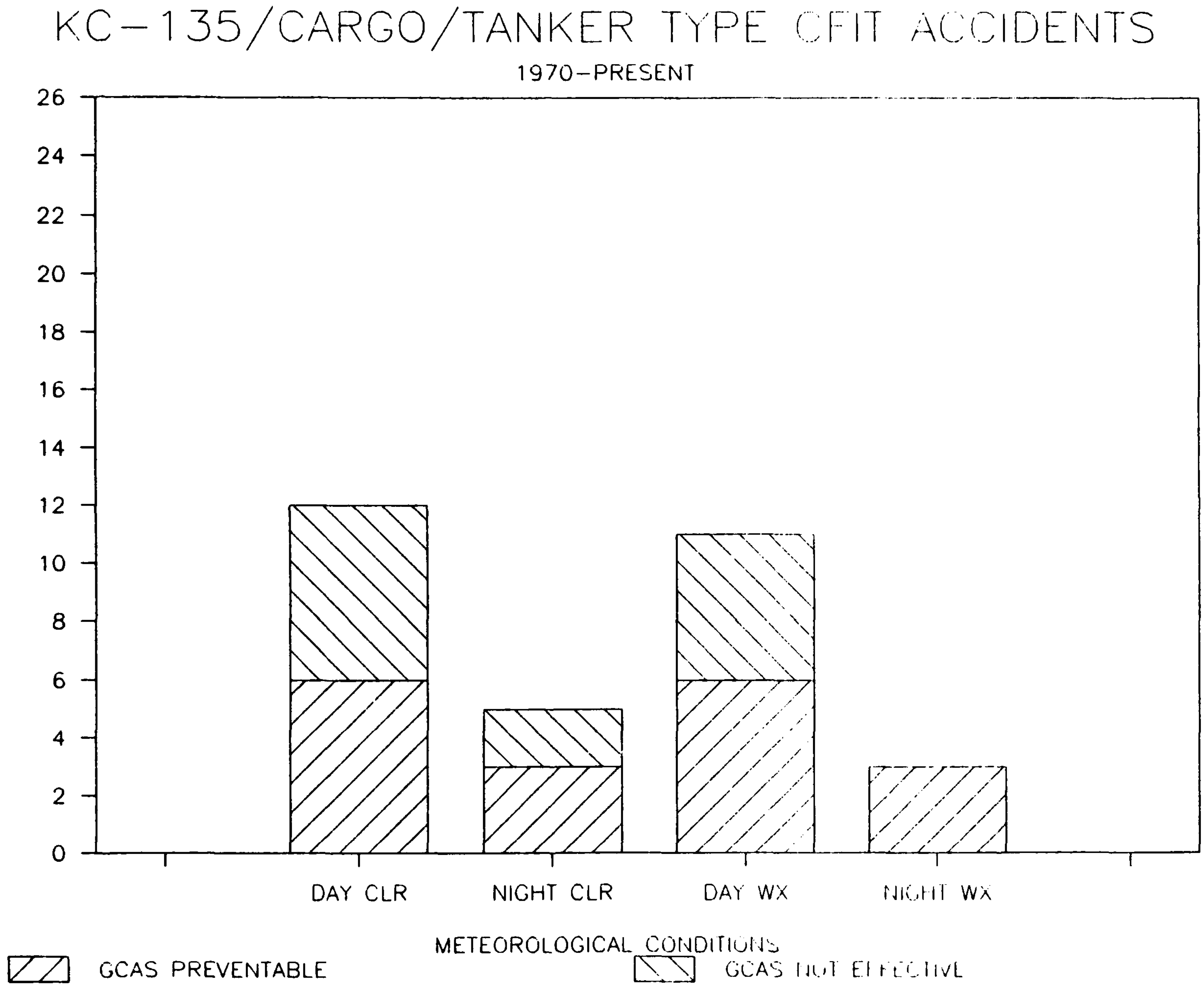

KC-135/CARGO/TANKER TYPE CFIT ACCIDENTS
1970-PRESENT
NUMBER OF ACCIDENTS
26
24
22
20
18
16
14
12
10
8
6
4
2
0
DAY CLR
NIGHT CLR
DAY WX
NIGHT WX
METEOROLOGICAL CONDITIONS
GCAS PREVENTABLE
GCAS NOT EFFECTIVE

Figure A-5

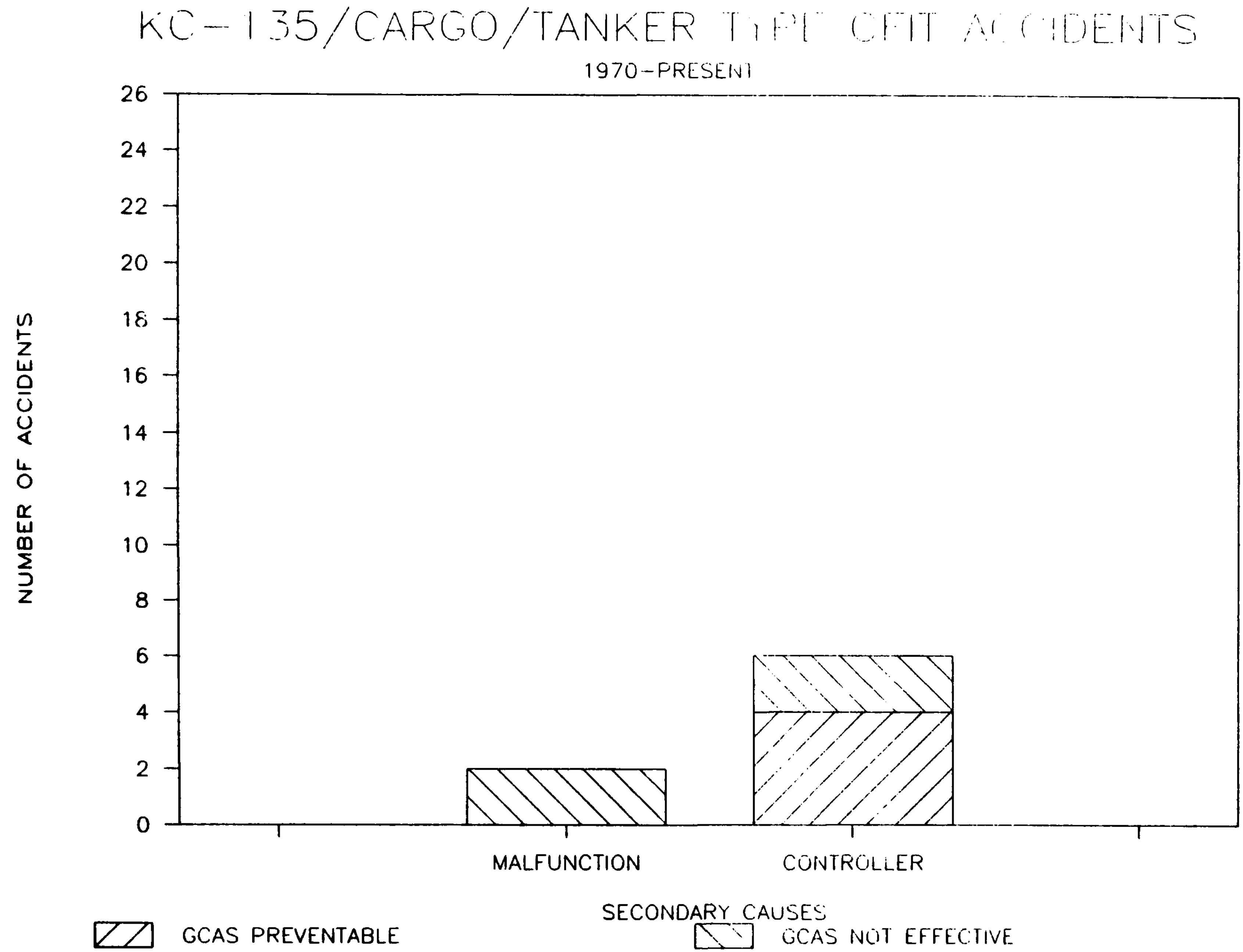

KC-135/CARGO/TANKER TYPE CFIT ACCIDENTS
1970-PRESENT
NUMBER OF ACCIDENTS
26
24
22
20
18
16
14
12
10
8
6
4
2
0
MALFUNCTION
CONTROLLER
SECONDARY CAUSES
GCAS PREVENTABLE
GCAS NOT EFFECTIVE

Figure A-6

APPENDIX B

GROUND COLLISION AVOIDANCE SYSTEM

QUESTIONNAIRE FOR

CARGO/TANKER TYPE AIRCRAFT

TANKER MODERNIZATION DIVISION
DIRECTORATE OF BOMBER/TANKER
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE,OHIO 45433-6503

PERSONAL DATA

Name (Optional):________________________________

Rank:________________________________

Aeronautical Rating:________________________________

Organization:________________________________

Office Symbol:________________________________

Duty Station:________________________________

Crew Position:________________________________

Total Flying Hours:________________________________

Total KC-135 Flying Hours:________________________________

Total Hours Current Crew Position:________________________________

Age:________________ **Sex:**________________

Describe any prior experience with Ground Collision Avoidance Systems (GCAS) or Ground Proximity Warning System(GPWS): ________________

GENERAL INFORMATION

1. Would you consider a Ground Collision Avoidance System (GCAS) to be beneficial for warning an aircrew of a possible ground collision?

(a) Yes
(b) No
(c) Maybe (Please explain in comments)

Comment(s):____

____

____

2. Which of the following GCAS warning modes would you consider as most effective in attracting an aircrew member's attention in a cockpit environment?

(a) Light
(b) Tone
(c) Voice
(d) A combination of light and tone
(e) A combination of light and voice
(f) A combination of tone and voice
(g) Other (Please specify)

Comment(s):____

____

____

3. Would you consider different GCAS modes (e.g., low level, takeoff, wind shear, etc.) that adjust for the different phases of flight as beneficial?

(a) Yes
(b) No
(c) Maybe (Please explain in comments)

Comment(s):____

____

____

4. Which of the following GCAS modes would you consider as beneficial? Select any or all of the answers that you think apply. If you feel mode(s) other than those listed is/are necessary, choose item (f) and specify in the comments section.

(a) Approach/Landing
(b) Low Level
(c) Rapid Descent
(d) Takeoff
(e) Wind Sheer
(f) Other (Please specify)

Comment(s):______________________________

____

____

5. Given the existence of different GCAS modes, please prioritize the following modes from most beneficial to least beneficial in the comments section? If you feel another mode is necessary, choose item (other) and specify what mode and why. (e.g., Approach/Landing 1, Low Level 2, Rapid Descent 3, Takeoff 4, Wind Sheer 5, Other (Over Water--because . . .) 6).

Approach/Landing
Low Level
Rapid Descent
Takeoff
Wind Sheer
Other (Please specify)

Comment(s):______________________________

____

____

6. Should the pilot be able to turn off the GCAS?

(a) Yes
(b) No
(c) Maybe

Comment(s):______________________________

____

____

7. What should the pitch limits of the GCAS be?

Minimum (Lower) limit ________ Maximum (Upper) limit ________

Comment(s):____

____

____

8. What should the roll limits of the GCAS be?

Minimum (Lower) limit ________ Maximum (Upper) limit ________

Comment(s):____

____

____

9. Should the GCAS extrapolate beyond the range of the radar altimeter?

(a) Yes
(b) No

Comment(s):____

____

____

10. What should the maximum altitude coverage of the GCAS be?

(a) Maximum coverage of the radar altitude.
(b) 5000 feet
(c) 10,000 feet
(d) Maximum altitude (ceiling) of the aircraft.

Comment(s):____

____

____

11. What should the GCAS minimum descent altitude (altitude where the GCAS warning is inhibited) be?

(a) 0 feet
(b) 50 feet
(c) 100 feet
(d) 200 feet
(e) Other (please specify)

Comment(s):____

VISUAL MODE

1. What type of light would you consider to be most beneficial in alerting the aircrew of a possible ground collision?

(a) Flashing
(b) Steady
(c) Other (Please specify)

Comment(s):____

2. What nomenclature should be printed on the warning light?

(a) Altitude
(b) Climb
(c) GCAS
(d) Pull up
(e) Recover
(f) Other (Please specify)

Comment(s):____

3. How long should the warning light be present?

(a) 1 second (s)
(b) 2 s
(c) 3 s
(d) 4 s
(e) 5 s
(f) As long as the warning condition exists.
(g) Other (Please specify)

Comment(s):____

4. If a flashing light is chosen, what time interval between warnings would you consider optimal (e.g., light, 1 second interval, light)?

(a) .1 s
(b) .5 s
(c) 1.0 s
(d) Other (Please specify)

Comment(s):____

AUDITORY MODE

TONE WARNING

1. What type of tone would you consider to be most beneficial for alerting the aircrew of a possible ground collision?

(a) Intermittent
(b) Steady
(c) Wavering
(d) Alternating between steady and wavering tone
(e) Other (Please specify)

Comment(s):____

2. How long should each warning signal be present?

(a) 1 second (s)
(b) 2 s
(c) 3 s
(d) As long as the warning condition exists.
(e) Other (Please specify)

Comment(s):____

____

____

3. For an intermittent tone, what time interval between warnings would you consider optimal (e.g., tone, 1 second interval with no tone, tone)?

(a) .1 s
(b) .5 s
(c) 1.0 s
(d) Other (Please specify)

Comment(s):____

____

____

VOICE WARNING

1. What type of voice should it be?

(a) Computerized female
(b) Computerized male
(c) Human female
(d) Human male
(e) Other (Please specify)

Comment(s):____

____

____

2. What voice message would you consider to be most effective in alerting the aircrew of a possible ground collision?

(a) Altitude
(b) Climb
(c) Pull up
(d) Recover
(e) A combination of two or more messages listed above (Please specify)
(f) Other (Please specify)

Comment(s):____

3. How many times should the voice warning be presented?

(a) One (e.g., altitude)
(b) Two (e.g., climb, climb)
(c) Three (e.g., pull up, pull up, pull up)
(d) Until the conditions to affect recovery are completed.
(e) Other (Please specify)

Comment(s):____

4. What time interval between warnings would you consider optimal (ex: "Recover", 1 second interval, "Recover")?

(a) .1 s
(b) .5 s
(c) 1.0 s
(d) Other (Please specify)

Comment(s):____

MINIMUM ACCEPTABLE CLEARANCE ALTITUDE

The Minimum Acceptable Clearance Altitude (MACA) graph is on the following page. This graph represents the relationship between what a pilot feels is the minimum acceptable clearance altitude (Above Ground Level-AGL) given the aircraft's downward vertical velocity (Vz). MACA is the lowest altitude (AGL) that an aircraft reaches during recovery from the initial GCAS warning for which a pilot feels minimum stress. For example, if the alarm sounds with a Vz of 600 feet per minute (fpm), the minimum acceptable clearance altitude for a given pilot might be 150 feet (AGL), whereas, at a Vz of 6000 fpm, it might be 1000 feet. (This is only an example, the numbers do not reflect any sort of experimentally collected data.) We would like you to draw a line that best approximates your minimum acceptable clearance altitudes for the given downward vertical velocity onto the graph. Please give this careful consideration and take enough time in drawing the line. Please draw directly on the graph and answer the following question.

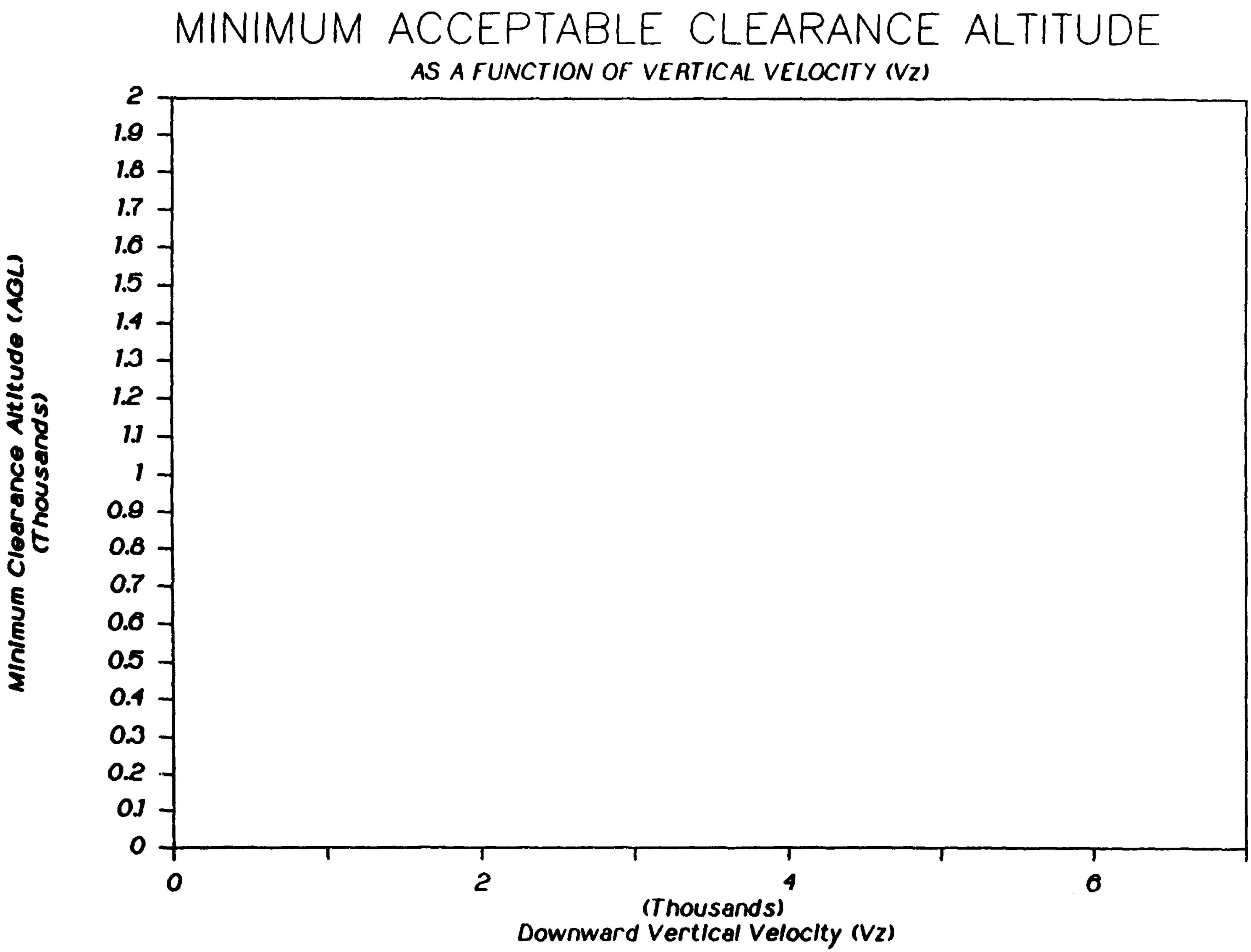
1. Do you fully understand what the minimum acceptable clearance altitude is and how to draw it onto the graph?

(a) I fully understand what MACA is and how to plot it.
(b) I fully understand what MACA is but am uncertain how to plot it.
(c) I do not understand what MACA is and am uncertain how to plot it.
(d) Other (Please specify)

Comment(s):____

____

____


MINIMUM ACCEPTABLE CLEARANCE ALTITUDE
AS A FUNCTION OF VERTICAL VELOCITY (Vz)
Minimum Clearance Altitude (AGL)
(Thousands)
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
(Thousands)
Downward Vertical Velocity (Vz)

APPENDIX C

PILOT GCAS QUESTIONNAIRE

1. In your opinion, the overall ground clearance provided by this Ground Collision Avoidance System (GCAS) algorithm was:

a. Too high.

b. Slightly high.

c. About right.

d. Slightly low.

e. Too low.

Comments:____

2. This GCAS algorithm applied its warnings:

a. Very consistently.

b. Consistently.

c. Inconsistently.

d. Very inconsistently.

Comments:____

3. How should the warning be mechanized? From the time of warning to:

a. One iteration of the warning.

b. Two iterations of the warning.

c. Until the aircraft's flight path is level with terrain (radar vertical velocity = 0).

d. Until some positive radar vertical vertical velocity is attained.

e. For as long as the warning conditions exist.

Comments:____

4. What type of warning(s) do you think would be best for this GCAS?

a. Light

b. Tone

c. Voice

d. Combination of light and tone.

e. Combination of light and voice.

f. Combination of tone and voice.

Comments:____

5. In your opinion, the job of a ground collision avoidance system is done when :

a. The pilot is made aware of the situation.

b. The pilot initiates corrective action.

c. A flight path level with the terrain is attained.

d. A positive radar altitude rate is achieved.

Comments:____

6. How confident are you in this Grt ɪd Collision Avoidance System algorithm?

a. Very confident.

b. Confident.

c. Not confident.

d. No confidence.

Comments:____

7. In your opinion, this algorithm you've just flown is suitable for:

a. Training missions only.

b. Peacetime operational missions.

c. Combat operations.

d. All of the above.

e. None of the above.

Comments:____

8. In your opinion, would the KC-135 aircraft fleet benefit from the use of the Cubic GCAS Algorithm? (Please explain why or why not.)

a. Yes

b. No

c. Maybe.

Comments:____

9. Please rate the overall performance of the KC-135 simulator operation.

a. Excellent .

b. Good.

c. Fair.

d. Poor.

Comments:____

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